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Early Growth & Yield Response to Various Two-Stage Tending and Harvesting Treatments

by

Darren John Wade Aitkin ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of **Master of Science**

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University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Early Growth & Yield Response to Various Two-Stage Tending and Harvesting Treatments** by **Darren John Wade Aitkin** in partial fulfillment of the requirements for the degree of **Master of Science** in **Forest Biology and Management**.

Abstract

Four variations of two-stage tending and harvesting systems were compared to evaluate differences in growth and yield characteristics between the treatments. The two-stage tending and harvesting treatment in this document refers to the removal of a trembling aspen (*Populus tremuloides*) overstory while protecting the white spruce (*Picea glauca*) understory, with intent to harvest the spruce and any additional regeneration in the second-stage harvest. A number of hypotheses are investigated in this document using data collected from these harvest areas. The white spruce residual cohort early response to release is compared between treatments; the regeneration cohort yield and density are compared between treatments; and the two-stage tending and harvesting systems are modeled and simulated to produce future estimates of yield and density.

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Chapter 1

INTRODUCTION

1.1 Introduction

Growth and yield are concepts often used in the study of forestry. They refer to the measure of the characteristics that are in the forest today and the change that will occur in the forest into the future. When management activities are conducted the growth and yield of a forest stand can be affected. This affect can often be a direct objective of management. With a better understanding of the growth and yield consequences of management decisions one can make more informed choices. This thesis explores the early growth and yield response to variations of the two-stage tending and harvesting treatment in the lower foothills boreal forest (Rowe 1972). Chapter 2, of this thesis, investigates the growth and yield response of the residual cohort following treatment. Chapter 3, of this thesis, investigates the establishment and growth in the early stages following treatment of a regeneration cohort. Chapter 4, of this thesis, investigates expected future stand volumes and densities of empirically based projections and treatment simulations. All of these component chapters contribute to the evaluation of the various treatments in question.

1.2 Two-Stage Tending and Harvesting

As a result of succession in the lower foothills boreal forest, it is common to see an immature white spruce (*Picea glauca*) understory paired with a dominant trembling aspen (*Populus tremuloides*) overstory (Rowe 1972). The utilization of both the timber resources (understory and overstory) has become a focus of the mixedwood management paradigm. One tending and harvesting scenario, which is prominent in this paradigm, is the two-stage tending and harvesting system (Brace and Bella 1988).

This system involves the growth and utilization of aspen and spruce on the same landbase. Brace and Bella (1988) suggested that with a stand of 80-100 year old trembling aspen overstory and 40-60 year old white spruce understory, one could potentially harvest the aspen overstory while protecting the immature spruce understory. The white spruce would experience a release effect, firm up to its new growing conditions and realize an increase in growth rate. Trembling aspen regeneration would recruit among the residual white spruce trees and in about another 60-80 years there would be a crop of mature (100-120 yrs old) spruce trees mixed in with mature (60-80 yr old) aspen trees for harvest. Some advantages and limitations to this form of two-stage tending and harvest are outlined by Brace Forest Services (1992) as follows:

Advantages of the model could include:

a) reduction or avoidance of the cost and risks associated with establishing and growing spruce on mixedwood cutovers,

b) improved utilization of aspen and increased spruce AAC through increased growth and shorter rotations for spruce released from the understory,

c) demonstration of the maintenance of mixedwood landscape aesthetics, wildlife habitat, recreational values and biodiversity thereby addressing major shortcomings of the clearcutting system as now practiced on many mixedwood sites,

d) contribution to solving the problems created where hardwood and conifer harvesting rights are held by different companies on the same land base, and where protection of understory spruce is a priority for the softwood users.

Some current limitations of the model include:

a) uncertainty about the feasibility of adapting available harvest technology to protect understory across a range of stand age, density and site conditions,

b) potential for windthrow of released spruce particularly on moist sites, and the risk of leader- weevilling in released spruce,

c) inadequate density and stocking criteria for mixed stands of protected spruce and aspen regeneration following the first harvest, and lack of knowledge of growth and yield and AAC implications for such mixed stands prior to the second harvest.

Brace Forest Service (1992)

With this summary it is apparent how mixedwood management in the form of understory protection and partial cutting is important and challenging. There are endless variations on how this two-stage model could be carried out, of which only a few may produce desired results. Much work is required to test different applications of two-stage models to find out under what circumstances, if any, this is a viable option that forest managers can reliably implement.

This thesis' focus is on stands with a spruce understory and an aspen overstory. This is a prominent stand structure to consider, in the lower foothills region, as it is estimated that a *'significant'* spruce understory exists in eighty percent of stands inventoried as hardwood or hardwood-softwood in this area (Brace and Bella 1988).

Four variations on the two-stage tending and harvesting scenario (Brace and Bella 1988) were carried out on stands consisting of a ninety year old trembling aspen overstory and a sixty year old white spruce understory in the lower foothills region of Northern Alberta (Navratil et al. 1994). These harvesting treatments are a part of the "Hotchkiss River Mixedwood Management Demonstration Area" (MacIsaac et al. 1999). This study is located in North Western Alberta, less than a hundred kilometres

northwest of Manning, which is located approximately a hundred kilometres northwest of Peace River. For a detailed description of how to find the study area see Appendix IV (Field Location). The four selected operational-scale harvesting treatments provide varying degrees of release and protection to the understory white spruce cohort.

1.3 Response to Release

For the purposes of this thesis, release refers to the removal or alteration of environmental conditions that constrain growth. Specifically, the removal of overstory trees that limit the light resource available to an understory tree results in the release of that understory tree. In the lower foothills boreal forest, understanding release is important because it provides more management options such as the utilization of understories. Response, for the purpose of this thesis, is the change in growth rate resulting from release. So, interest lies in evaluating the response to release in the residual cohort of the various treatments.

A number of studies in various forest types have shown that significant response to release of individual trees can be experienced following thinning or overstory removal (examples: Bella and Gal 1996, Carlyle 1998, Hynynen 1995, Pukkala et al. 1998, Urban et al. 1994, Yanai et al. 1997, Youngblood 1991). However, further testing is required to see if certain operational treatments can be carried out with net stand level yield benefits.

Following release, new microclimate conditions are present in a stand. This change in microclimate can be of benefit to individual trees, with the supply of more available resources; or it can cause an individual tree stress, as it may not be equipped to deal with an abundance of additional resources. Any change in microclimate can result in stress to trees (Greene et al. 1999). One of the obvious changes to microclimate for an individual tree following overstory removal is the increase in light availability. Some of the other changes that will occur relate to exposure to wind, temperature variations, water relations and nutrient availability. The significance of these microclimate changes is largely dependent on site conditions and the removal intensity.

One resource that could potentially cause a tree physiological stress is light (Hale and Orcutt 1987). If a tree has developed primarily in the shade and contains a large number of shade-adapted leaves, when it's light environment changes to full light, these shade leaves will be damaged and likely will die. Donner and Running (1986) refer to this initial reduction in leaf area as "thinning reduction". Shade leaves have different components than sun leaves resulting in lower compensation points and ultimately higher photosynthetic rates than sun leaves in low light. These same characteristics make high light levels fatal to the shade leaves, as shade leaves have a limited capacity to adjust to high light intensities

(Hale and Orcutt 1987, Oliver and Larson 1990). In the extreme case where a suppressed understory tree is introduced to full light the heat scorching and bleaching of leaves may kill the majority of its foliage from which it may not recover (Oliver and Larson 1990). In the event that most of a tree's leaves are killed by high light there is still a potential for a flush of new ones in the same season. Most deciduous trees and some evergreen trees are able to have a second flush of foliage (Oliver and Larson 1990). This ability to have a second flush of foliage is one way that a tree can survive through the increased light and heat of release.

It is not only the leaves that experience heat scorching. Under hot and dry conditions stems will show increased respiration, thus using up photosynthates. In extreme cases when stems are exposed to direct sun in hot dry conditions heat scorching will occur, damaging the cambium (Hale and Orcutt 1987, Oliver and Larson 1990). This damage, if it does not kill the tree, will require additional resources to replace killed or damaged branches.

Physical damage to residual trees can be a major cause of stress. The probability of wind damage increases for released trees, which developed in a dense stand and have been exposed by thinning or a partial cut treatment (Matthews 1989). Trees with smaller crowns and a greater diameter to height ratio tend to have fewer problems with wind than trees with the opposite characteristics. The crown characteristic that promotes reduced wind damage (small crown) is just the opposite of the characteristic that promotes the largest growth response to release (long crown). The response of a vigorous crown expansion may result in a 'top-heavy' tree, which may be more susceptible to stem breakage (Oliver and Larson 1990). The increased biomass allocation to root growth following thinning (Urban et al. 1994, Donner and Running 1986) is one mechanism that decreases the chance of blow down.

Temperatures in the stand tend to have a greater range with increased removal intensity (Groot and Carlson 1996). With less residual trees in a stand direct irradiance to the ground is greater resulting in higher daytime high soil temperatures. Less residual trees also means more heat loss in the night resulting in lower nighttime low temperatures. The variation in this effect between the various two-stage tending and harvesting treatments would likely be minimal. An increase in soil and crown temperatures does not only have negative implications. Gillespie and Hocker (1986) noted that an increase in temperature allowed for early seasonal growth initiation and increased the response to thinning for white pine (*Pinus albicaulis*).

Soil moisture and a tree's water relations will also be affected by a change in the overstory density. The response of residual trees to this change in water relations will be most significant in sites where water is limiting. Gillespie and Hocker (1986) found, in white pine stands where growing season is limited by

soil moisture, that soil moisture was greater in recently thinned stands, thus creating the opportunity for more growth in a given season. Another study comparing the water potential in thinned lodgepole pine (*Pinus contorta*) stands and controls found that thinning improved site water relations by reducing stand transpiration, crown interception, and live root density with in the soil (Donner and Running 1986). This increased water for residual trees resulted in decreased water stress, increased carbon acquisition and increased growth. Note that Donner and Running (1986) conducted this lodgepole pine study in stands where water was a limiting factor. Thinning and partial cutting may have very little effect on water relations in situations where water is in abundance, which is the case in the study area, as the treatments were carried out in moist to wet sites.

Similar to water, when nutrients are limiting there is a potential to increase availability by thinning. Thinning reduces the number of trees competing for a limited nutrient pool, thus, increasing the availability to the residual tree. Another mechanism by which availability is increased is residue retention. Residue retention refers to leaving the foliage and branches of the removed trees on the site. Both of these mechanisms result in increased nitrogen mineralization (Carlyle 1998 and Hynynen 1995). Under circumstances where nitrogen is limiting a thinning event may help its availability but combining it with a fertilizer treatment is an even more aggressive management option to consider.

Following a thinning the occupied growing space in a stand decreases. This growing space is then gradually reoccupied as the crowns and root systems of the residual trees expand (Daniel et al. 1979, Oliver and Larson 1990). For the individual tree, lag-time to release (Yang 1989, Youngblood 1991, Urban et al. 1994) or failure to release has been attributed to a number of stresses: stress due to wind, temperature, and sun. Other factors involved that are difficult to measure are genetics, length of suppression, root grafting (Gillespie and Hocker 1986), and phenology (example: tracheid size). Following release, individual trees may allocate resources to roots, either for repair or storage, thus, deferring carbon resources from diameter growth (Urban et al. 1994). This type of carbon economics can make a tree's response complex. As a tree gains resources such as light the tree has mechanisms to allocate this new available carbon to its crown, roots and/or trunk. Adding to the crown would allow for an increased carbon acquisition capability; adding to the roots would allow for increased nutrient and water uptake as well as provide for an increased wind-firmness; and finally adding to the trunk is ultimately what the timber oriented forest manager wants to see with accelerated merchantable volume accumulation. It was observed that additional carbon was allocated largely to the roots and crown, to fill the space that was once occupied by neighbouring trees (Donner and Running 1986, Oliver and Larson 1990). Investment of this additional photosynthate in leaf area results in accelerated carbon acquisition and in the long run increased stem growth. All of the above variables help determine to what extent a tree will respond and how long it will take to respond.

Chapter 2 addresses the early response of the residual white spruce trees to various two-stage tending and harvesting treatments. It makes comparisons of individual tree characteristics and stand level characteristics five years following the first-stage of the treatments.

1.4 Regeneration Recruitment

With the two-stage tending and harvesting system, growing space is made available during the first-stage. Due to the nature of regeneration in stands of this type in the lower foothills boreal forest the growing space is quickly reoccupied by a vigorous recruitment of trembling aspen, balsam poplar and white birch. In addition to the suckering hardwoods some softwoods are also expected to make use of this excess growing space. This vigorous regeneration cohort is a major component to the success of this type of harvesting system.

With a partial cut treatment the microclimate at the ground level will be altered providing optimum conditions for vigorous trembling aspen, balsam poplar and white birch suckering and potential seedbeds for white spruce germinates. The increased soil temperature may encourage regeneration or suckering (Oliver and Larson 1990) of tolerant or intolerant species depending on ground light levels. This cohort of trees is expected to provide a significant proportion of the yield come the second-stage harvest, thus, it is important to understand the levels of regeneration which can be expected following the first stage harvest. Greene et al. (1999) suggests that currently more research is needed to better predict natural regeneration under a partial cut system.

Kobe and Coates (1997) formulated a mortality model for saplings based on their survival in relation to recent growth. They argue that in low light environments the abundance of regeneration by species is determined by their ability to survive not grow. Thus, the characteristics of tolerant and intolerant species allow for a mix in the regeneration cohort depending on the available light in relation to the residual trees. As the residual layer is not expected to significantly impede the survival of the new regeneration trees, trembling aspen and balsam poplar, both intolerant species, are expected to dominate this layer.

Chapter 3 addresses the early response of the regeneration cohort to the various two-stage tending and harvesting treatments. It makes comparisons of individual tree heights and stand level densities five years following the first-stage of the treatments.

1.5 Harvest Treatment Modeling

Decision-making by forest managers is driven and restricted by what is known about the present and future forest yields. The importance of knowing present yields and being able to estimate future yields,

both for natural stands and for managed stands, is evident. As demand for more complex harvesting strategies increase, with thoughts of improved utilization and the retention of more 'natural' stand structures, the need for growth models that are sensitive to treatment growth response are becoming more of a focus. Some studies have tried to model response to release in various treatments as a function of change in 'competitive stress index' (Smith and Bell 1983), initial diameter, competition index ("zone of influence"), crown class (Gillespie and Hocker 1986), and time since treatment.

Chapter 4 outlines the methods and results of projections made to estimate what conditions will exist for the second-stage harvest based on empirical treatment data. A simulation is also made modeling the entire two-stage tending and harvesting treatment from first germination to final harvest.

All projections and simulations in this study are made using the Mixedwood Growth Model (MGM). This model is a distance independent individual-tree stand growth model (Titus 2002). This model was not developed with empirical treatment response data; rather it was developed with natural stand permanent sample plot (PSP) data. Even though treatment data were not used in the model's development the height, diameter increment and mortality models which form the basis of MGM should reasonably be able to model a stands post treatment growth, as characteristics such as competitive status and individual tree size, which drive the growth functions, are expected to have similar influence both in managed stands and in natural stands. Chapter 4, of this thesis, investigates how well MGM models the two-stage tending and harvesting system.

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Chapter 2

RESIDUAL COHORT GROWTH & YIELD

2.1 Introduction

This chapter explores the early growth and yield variation in the residual white spruce (*Picea glauca*) cohort of three two-stage tending and harvesting scenarios. There are two levels, at which treatment response can be addressed: the individual-tree level and the stand level. This chapter first addresses individual tree characteristics by presenting a statistical comparison of two characteristics between treatments. These characteristics are height and diameter at breast height (dbh), as these are typically used to evaluate the growth and yield of trees. This chapter goes on to present a stand level comparison between treatments. Density and volume per hectare are the stand level characteristics estimated to depict what is occurring at this level.

The following specific questions are addressed in this chapter:

- Is there a significant difference in the early individual-tree yield characteristics (height and diameter) of the residual white spruce trees between treatments?
- Is there a significant difference in the early individual-tree growth characteristics (height increment and diameter increment) of the residual white spruce trees between treatments?
- Is there a significant difference in the density of the residual white spruce cohort between treatments?
- Is there a significant difference in the early residual white spruce stand-volume characteristics (m^3/ha, m^3/ha/year) between treatments?

2.2 Methods

2.2.1 Harvesting Treatments

The harvesting treatments are strip treatments established north south, perpendicular to prevailing winds. The strips are made up of machine corridors, residual strips (understory protection strips), and buffer strips. Typical machine corridors are eight metres in width. Fellers removed all trees in the machine corridors and then created the residual strips, with their approximate six-metre reach, on either side of the corridor. In the residual strips all mature trembling aspen and balsam poplar (*Populus balsamifera*) and any merchantable spruce trees are removed and the immature spruce are left. The three treatments addressed in this study are; one-pass uniform modified shelterwood, two-pass alternating

fifty metre strips and two-pass alternating one hundred metre strips. Note that there is a fourth treatment, which is not being considered here due to its lack of residual trees. The fourth treatment is a clearcut treatment and will be examined at in Chapter 3 and Chapter 4.

One-Pass Uniform Modified Shelterwood ('Mod Shelter')

The one-pass uniform modified shelterwood ('Mod Shelter') has machine corridors spaced twenty-five metre centre-to-centre. Thus, resulting in a repeated pattern of an approximately eight-metre wide machine corridor, a six-metre wide understory protection area, and a five-metre buffer where no trees were removed. The five-metre buffer is the area between machine corridors, which could not be reached by feller-bunchers. The buffer strips represent an estimated loss of 15% merchantable deciduous volume that will be left in the block (Navratil et al. 1994). This treatment is thought to provide a high level of understory white spruce protection, with an average distance to buffering of ten-metres. For treatment diagrams and aerial photos see Appendix I (Treatment Summary).

Two-Pass Alternating Strip Cuts ('50m Strip' & '100m Strip')

The fifty-metre ('50m Strip') and hundred-metre ('100m Strip') two-pass alternating strip cuts provide less protection for understory white spruce trees than the 'Mod Shelter' treatment. The treatment areas are divided into one hundred and two hundred metre wide strips respectively. The windward leading half of the strip is not harvested in the first pass. The alternate half of the strip (50m and 100m respectively) is harvested with a repeated pattern of machine corridors 20m centre to centre, resulting in a repeated pattern of 8m machine corridors and 12m residual strips across the 50m and 100m strips. The windward leading half of the strip is then cut five years after first harvest in the same pattern. The '50m Strip' and '100m Strip' treatments are considered to have moderate to low wind protection for residual trees (Navratil et al. 1994), as the average distance to aspen buffering are twenty-five metres and fifty metres respectively. Following the second pass, when the other strip is removed both the '50m Strip' and '100m Strip' treatments will experience reduced wind protection due to the dramatic reduction in aspen residual tree buffering. The residual trees in the first strip and the understory white spruce in the second strip will undergo morphological changes due to exposure following first pass; these morphological changes may increase their chances of survival following second pass, where more exposure and release is introduced. The intent of these treatments is to let the residual white spruce trees experience a gradual exposure to release in order to increase the probability of survival and avoid the stress that immediate full exposure is more likely to present. For treatment diagrams and aerial photos see Appendix I (Treatment Summary).

Control Block

A control block was included in this study. The control is an uncut stand, which resembles pre-harvest conditions. All four treatments and the control provide a gradient of residual white spruce release and

protection. To quantify the level of residual tree protection, one could use the average distance to a windward buffering agent (Table 2-1).

Table 2-1: Average distance to nearest windward buffering agent

Treatment	Distance to buffer following 1st pass	Following 2nd pass
'Uncut Control'	0m	NA
'Mod Shelter'	~10m	NA
'50m Strip'	~25m	~150m
'100m Strip'	~50m	~400m
'Clearcut'	~500m	NA

2.2.2 Sampling and Measurement

As this experiment is a long-term one and interest lies in measuring the yield of individual trees over time, permanent sample plots (PSP) were used as the method of data collection. PSPs, 0.06ha in size, were randomly established within the machine corridors and the residual areas in each treatment and the control. In total fifty-two PSPs were established at the beginning of the fifth growing season following treatment (1998). PSPs in the residual areas included measurement of all trees taller than 1.3m. Measurements such as height, dbh, height to crown base, crown diameter, and damage codes were recorded for all species. Cores were extracted from white spruce trees so breast height age could be calculated. For a detailed description of sampling and measurement procedures see Appendix II (Sampling and Measurement).

In the sixth growing season (1999) one third of the original trees were measured again in order to ensure an accurate base line for future measurements and to assess the growth of trees in the "fifth growing season". The fifth growing season refers to the fifth season since harvesting treatment. In 1999, white spruce cores were also collected from a sub-sample of white spruce trees in each treatment in order to assess early diameter increment response. The previous 10 annual increments were measured with an electronic microscope core increment-measuring device.

Independent of this study, the Canadian Forest Service (CFS) conducted some sampling in the same treatment areas. CFS established transects throughout the treatments providing detailed immediately pre- and immediately post-treatment yield information. These data were useful for stand level analysis and provided information at the strip level on immediate post treatment conditions. For a more detailed description on the layout of the transects see Navratil et al. (1994).

2.2.3 Analysis

In order to evaluate the growth and yield characteristics of the harvesting treatments, analysis was conducted at two levels; the individual tree level and the stand level. For this analysis a number of

testing techniques were utilized, accompanied by their associate assumptions. Pseudoreplication, analysis of variance, nesting, covariate analysis and Tukey Studentized range multiple comparisons are all concepts and methods relevant to this chapter.

Summary Statistics

The individual tree summary statistics of the PSP data used for treatment analysis is presented in Table 2-2. The plot level summary statistics for volume and density are presented in Table 2-3. Some jack pine (*Pinus banksiana*) occurred naturally in the treatment area and thus the occurrence of this species is summarized here as well.

Table 2-2: Height and diameter summary statistics

		Height (m)			DBH (cm)		
Treatment	Species	# of trees	Mean Height	Standard Deviation	# of trees	Mean DBH	Standard Deviation
'Uncut Control'	Hwd*	90	22.18	2.65	90	22.34	4.23
	Pj	3	26.07	1.54	3	36.47	4.57
	Sw	76	12.02	5.24	76	12.96	6.63
'Mod Shelter'	Hwd*	229	20.02	6.23	229	22.39	8.91
	Pj	13	23.37	2.92	13	29.69	5.68
	Sw	270	8.79	6.30	270	10.39	8.30
'50m Strip'	Hwd*	55	17.40	3.80	55	18.21	5.22
	Pj	3	21.17	4.65	3	29.37	10.76
	Sw	147	12.00	5.35	147	14.21	7.37
'100m Strip'	Hwd*	55	13.24	8.77	58	14.04	10.55
	Pj	0	0.00	0.00	0	0.00	0.00
	Sw	115	10.20	5.50	121	13.13	7.57

* The Hwd species category includes Aw, Pb and Bw.

This chapter checks for significant differences in these mean individual tree heights and dbhs between the various treatments. Likewise, tests were conducted to check for significant differences between the mean stand level volume and density characteristics for the various treatments.

Table 2-3: Plot level volume and density summary statistics

			Volume (m^3/ha)		Density (stems/ha)	
Treatment	# of plots	Species	Mean Volume	Standard Deviation	Mean Density	Standard Deviation
'Uncut Control'		Hwd*	279.47	16.47	750.00	117.85
	2	Pj	27.43	4.06	25.00	11.79
		Sw	69.20	8.94	633.33	47.14
'Mod Shelter'		Hwd*	156.41	26.07	367.35	112.29
	8	Pj	14.53	30.22	20.85	39.37
		Sw	38.42	16.74	433.13	212.40
'50m Strip'		Hwd*	21.77	29.10	99.43	111.87
	7	Pj	3.81	5.61	6.86	9.44
		Sw	35.81	16.39	265.71	118.88
'100m Strip'		Hwd*	25.90	32.43	101.56	105.98
	8	Pj	0.00	0.00	0.00	0.00
		Sw	27.63	17.35	274.90	166.52

* The Hwd species category includes Aw, Pb and Bw.

Pseudoreplication

In order to perform statistical tests to evaluate the treatments for significant differences, replicates of the experimental units are required. With landscape level ecological experiments, true replication is often not possible due to the scale of the experimental units and the cost to implement treatment; thus, restricting experiments to small local populations and environmental conditions. Pseudoreplication is another valid option. Two assumptions must accompany statistical tests with pseudoreplication; experimental units (harvesting blocks) are assumed to have identical origins; and the selection of the experimental units for treatment is assumed to be random (Hurlbert 1984). By utilizing the concept of pseudoreplication the plots become the experimental unit and thus provide replicates for statistical testing. The idea here is to provide inferences for this small local population, which can then be utilized as a starting point for decision making in similar populations.

Pseudoreplication is often used as a negative descriptor of a statistical analysis paired with an experimental design where the wrong hypothesis is being tested. As long as the narrow scope of the test is recognized, pseudoreplication is valid. However, it is not valid to make definitive conclusions with inferential statistics outside of the local level, using a pseudoreplicated design. A number of articles, since Hurlbert (1984) discussed and criticized the incorrect use of pseudoreplication, have been published discussing specific applications of the statistical technique (examples: Cilek and Mulrennan 1997, Skalaski 1995, Suomela and Ayres 1994, and Van Mantgem et al. 2001,).

Analysis of Variance

Analysis of variance (ANOVA) is the primary statistical test used throughout this chapter. A number of assumptions are made in the interpretation of ANOVA test results. We assume the treatments and the environmental effects are additive, and that the experimental errors are random, independent and normally distributed about a zero mean, with a common variance (Steel et al. 1997, p174). Following a visual assessment of the variables being tested the assumptions appear to be met.

Nesting

The concept of nesting was included in the analysis of mean height and dbh comparisons. Nesting was used to ensure the plot level variation was accounted for in the ANOVA tests. The assumption is that the individual trees in a plot are not completely independent of one another; therefore, the variation within the plot is expected to be less than the variation between plots. The nesting factor in the ANOVA test has a random effect on the mean being tested (Steel et al. 1997, p158).

Covariate

Height and dbh have a strong relationship with total age. In evaluating height and dbh, it is expected that some of the variation between treatments can be accounted for by considering the variation in total age between treatments; i.e. if stand 'a' has spruce trees with an average total age of 80 years and stand 'b' has spruce trees with an average total age of 40 years, one would expect that stand 'a' on average would have taller trees if all other conditions are the same. This variation in total age can be accounted for on an individual tree basis by including total age as a covariate when conducting an ANOVA test on mean height and dbh.

When a covariate is used the following assumptions are made: the independent variable observations are fixed, independent of treatment and measured without error; the regression between the independent variable and the dependent variable is linear and independent of treatment; and the residuals are normally and independently distributed with a mean of zero and a common variance (Steel et al. 1997, pp 433-434). A heterogeneous covariate was utilized, allowing a different linear height total age relationship for each treatment.

By including total age as a covariate, differences in height due to variation in tree total age between treatments is accounted for. The relationship between height and dbh, with total age is closer to a logarithmic relationship than a straight-line relationship. This relationship is most commonly represented by a sigmoid curve, as with the general configuration for most functions for tree growth (Avery and Burkhart 1983). In order to linearize the relationship the logarithm of height and dbh were utilized in analysis.

Means were adjusted to represent the relative mean logarithm of height and dbh at the overall average total age. Adjusted mean heights and dbhs can be calculated by way of natural logarithm transformation, making sure to correct for lognormal bias (Steel et al. 1997, pp 242-245). This correction is carried out with Equation 2-1.

Equation 2-1 $$Lognormal\ Mean = e^{\mu_x + 0.5\sigma_x^2} = e^{\overline{X}_i + 0.5MSE} = e^{\overline{\ln Y} + 0.5MSE}$$

Each treatment mean lognormal height has half of the mean sum of squares error (MSE) added to it and the antilog is taken. Total age standardized mean heights can then be compared between treatments.

Multiple Comparisons

The Tukey Studentized range test (HSD – honestly significant difference) is used for multiple comparisons throughout this chapter in cases where the corresponding ANOVA test is found to be significant. HSD allows paired comparisons to be made while controlling alpha inflation (Rosenberg 1990). Throughout this chapter an alpha (α) value of 0.05 is used to evaluate significance. Thus, the probability of a type I error, falsely rejecting the null hypothesis, is five percent.

2.3 Individual White Spruce Tree Response

Individual tree characteristics are an important measure of response to harvesting treatments. It is essential to recognize that all of the individual white spruce trees in the PSP sample are ones that were not cut during harvest due to any one of three reasons: 1) the tree was in a residual strip and was not of merchantable size; 2) the tree was in a residual strip, was of merchantable size, but was left due to its position in relation to other un-merchantable trees; or 3) the tree was in an uncut buffer strip. As the PSP measurements were taken five years following harvest, in addition to not being cut, the trees in the PSP sample are ones that survived following treatment.

Individual tree response can be addressed in a number of ways. From an operational standpoint, changes in carbon allocation cannot be measured easily; thus, tree characteristics that can be directly measured, such as height and dbh, will be used for the evaluation of individual tree response. By describing and comparing yield information we have one measure of individual response. This yield comparison does not necessarily represent a growth response to release, but will also reflect what treatment has been carried out. For instance, a treatment that retained a greater number of larger diameter residual white spruce trees will result in a greater average residual white spruce diameter; not due to growth response to release, but rather directly due to harvesting activities. To directly assess growth response to release this chapter uses a second form of assessment. By using the two measurements of these yield characteristics we can assess growth or periodic change in height and

diameter. Due to the timing of plot measurement, this change in height and dbh represents the fifth growing season following harvest treatment.

2.3.1 Individual White Spruce Height

The comparison of mean individual white spruce tree height allows us to evaluate a 'snap shot' of tree heights in the various treatments. Tree total age, as it relates to height, is used to bring the comparison to relative terms. Two subsections are discussed in this section: one discussing the results from an analysis of covariance (ANCOVA) for height yield and the other discussing the results from an ANOVA for height increment.

Height Yield ANCOVA

To compare the mean heights of residual white spruce trees between treatments and assess the significance of the differences an ANCOVA test is presented. The ANCOVA is conducting considering two sources of variation; the first, is the variation in height inherently introduced with total age variation and the second is the difference in variation in and between plots. The null hypothesis that is tested is that there is no difference in the mean height of residual white spruce trees between treatments. In order to test this hypothesis, an analysis of covariance (ANCOVA) was conducted on the natural logarithm of height with the germination total age as a covariate and with a nesting factor that saw plots nested in treatments.

The nesting and heterogeneous total age covariates were found to be significant (α=0.05). The mean height between treatments was not significant (Table 2-4); thus, we cannot reject the null hypothesis. The majority of the variation in height is accounted for with the variation in total age.

Table 2-4: ANCOVA for natural logarithm of height for residual white spruce between treatments

Source of Variation	Df	SSE	MSE	F		Pr>F
Treatment	3	0.6962	0.2322	$MSE_{(trt)}/MSE_{(Plot(trt))}$ =	0.29	.8295
Plot(trt)	22	17.3847	0.7902	$MSE_{(plot(trt))}/MSE_{(error)}$ =	7.43	<.0001
Age	1	147.0592	147.0592	$MSE_{(age)}/MSE_{(error)}$ =	1383.25	<.0001
Age*Trt	3	1.2277	0.4092	$MSE_{(age*trt)}/MSE_{(error)}$ =	3.85	0.0096
Error	575	61.1305	0.1063			
Total	604	428.8410				
R^2	CV	Root MSE	Mean			
0.8574	4.8977	0.3260	6.6572			

The mean heights and adjusted mean heights are presented in Table 2-5. The adjusted mean heights are based on a relative total age adjustment. Within each treatment the mean heights are adjusted to reflect the average predicted height of the average total aged tree; the average total age tree is 50 years.

This adjustment allows us to compare the adjusted mean heights between treatments on relative terms. There is very little difference in height between treatments, with the greatest spread between 8.2 metres and 9.79 metres for the '50m Strip' treatment and the 'Uncut Control', respectively. The adjusted mean heights account for the covariate's effect and the unequal sample size.

Table 2-5: Mean height of white spruce trees in the different harvesting treatments

Treatment	N	Mean Height (m)	Standard Deviations (m)	Adjusted Mean Height (m)	Mean Age (years)
'Uncut Control'	77	11.93	5.26	9.79	52.2
'Mod Shelter'	274	8.73	6.27	8.53	44.1
'50m Strip'	152	11.91	5.40	8.20	57.7
'100m Strip'	119	10.21	5.46	8.39	51.9

Height Increment ANOVA

To assess early white spruce growth, a test for significance of the mean height increment was conducted. This is of interest to get an indication of the early growth response of individual trees to the various treatments. The null hypothesis being tested is that there is no difference in mean height increment present between treatments. A nested ANOVA, where plots were nested in treatments, was conducted to test this hypothesis.

There was no significant (α=0.05) difference between mean height increment of the various treatments. The nesting of plots in treatments was found to be significant (α=0.05), indicating that the variation of individual white spruce tree height increment varied less within a given plot than they did between plots (Table 2-6).

Table 2-6: Nested ANOVA for height increment for white spruce residuals

Source of Variation	Df	SSE	MSE	F		Pr>F
Treatment	3	9773.6320	3257.8774	$MSE_{(trt)}/MSE_{(Plot(trt))}$ =	0.65	0.5962
Plot(trt)	17	85756.6054	5044.5062	$MSE_{(Plot(trt))}/MSE_{(error)}$ =	2.70	0.0006
Error	172	321231.9444	1867.6276			
Total	192	423296.1658				
R^2	CV	Root MSE	Mean			
0.2411	121.0376	43.2161	35.7047			

The mean single-season height increments for the various treatments are listed in Table 2-7. The relatively large measurement error contributes to the large standard deviations. These large standard deviations are evident while looking at the coefficient of variation for each treatment. The 'Uncut Control' and 'Mod Shelter' have large coefficient of variation values over 1.5.

Table 2-7: Mean height increment for the fifth growing season following treatments

Treatment	N	Mean Height Increment (cm)	Standard Deviation (cm)	Coefficient of Variation
'Uncut Control'	31	28	50.19	1.79
'Mod Shelter'	84	29	44.92	1.55
'50m Strip'	49	42	41.52	.99
'100m Strip'	29	53	53.84	1.02

2.3.2 Diameter at Breast Height Analysis

Diameter is typically thought to be more sensitive to release conditions than height. Diameter release does not often occur instantaneously following treatment. A 'lag-time' is often associated with growth release and corresponds with the time it takes an individual tree to adjust morphological characteristics to the new growing conditions (Klinka et al. 1992); such as increasing leaf area for better utilization of a newly abundant light resource. This section identifies and assesses the differences in diameter yield and release of residual white spruce, on an individual tree bases, following the harvesting treatments. Dissimilarities in dbh growth and yield can be assessed by comparing mean dbhs following treatment and by comparing the one-year diameter increment. In a further look at relative radial release, the diameter increment ratio expressing diameter increment after treatment relative to diameter increment before treatment is used.

Diameter at Breast Height Yield ANCOVA

To assess the radial growth treatment response, mean dbh between treatments is tested for significant differences. The null hypothesis tested here is that the mean diameter at breast height is the same in the various harvest treatments and the 'Uncut Control'. An ANCOVA, which included the nesting of plots in treatments and used tree total age as a covariate, is used to test for significant differences in the mean natural logarithm of dbh for residual white spruce trees between treatments.

The mean natural logarithm of dbh was not found to be significantly (α=0.05) different between treatments. The use of total age as a heterogeneous covariate is significant (α=0.05), as seen in the ANCOVA output (Table 2-8). Nesting is also significant (α=0.05) indicating that the variation within plots is less than the variation among plots for the natural logarithm of dbh.

Table 2-8: ANCOVA for the natural logarithm of dbh between treatments with total age as covariate

Source of Variation	Df	SSE	MSE	F		Pr>F
Treatment	3	4.2597	1.4199	$MSE_{(trt)}/MSE_{(Plot(trt))}$ =	1.38	0.2765
Plot(trt)	22	22.7150	1.0325	$MSE_{(Plot(trt))}/MSE_{(error)}$ =	4.27	<.0001
Age	1	235.3673	235.3673	$MSE_{(age)}/MSE_{(error)}$ =	973.41	<.0001
Age*trt	3	4.1649	1.3883	$MSE_{(age*trt)}/MSE_{(error)}$ =	5.74	0.0007
Error	581	140.4835	0.2418			
Total	610	772.4178				

R^2	CV	Root MSE	Mean
0.8181	23.5135	0.4917	2.0912

The actual and adjusted mean dbhs are shown in Table 2-9 below. Adjusted means represent least square means of dbh for each treatment as with the consideration of the covariate, total age. This allows us to compare the estimated mean dbh at the overall average total age (50 years). The adjusted means are also adjusted to account for the unbalanced design.

Table 2-9: Mean diameter at breast height comparison

Treatment	N	Mean DBH (cm)	Standard Deviations (cm)	Adjusted Mean DBH (cm)
'Uncut Control'	77	12.87	6.63	10.53
'Mod Shelter'	274	10.33	8.26	9.62
'50m Strip'	152	14.14	7.49	9.71
'100m Strip'	125	13.14	7.48	10.40

Diameter at Breast Height Increment ANOVA

In order to compare diameter growth rates, the individual tree diameter increments in the fifth growing season following treatment were derived and the treatment mean residual white spruce diameter increments were compared. The null hypothesis being tested is that there is no difference in residual white spruce dbh increment in the fifth growing season following treatment. A nested ANOVA is carried out to test for significant (α=0.05) differences in mean dbh increment between treatments.

The nesting is significant (α=0.05) and thus the variation within plots is less than the variation among plots. Mean dbh increment is significant (α=0.05) between treatments (Table 2-10); thus, we must reject the null hypothesis and conclude that at least one mean diameter increment is significantly (α=0.05) different than another.

Table 2-10: Nested ANOVA for dbh increment for white spruce residuals

Source of Variation	Df	SSE	MSE	F		Pr>F
Treatment	3	4.1698	1.3899	$MSE_{(trt)}/MSE_{(Plot(trt))} =$	4.69	0.0117
Plot(trt)	21	6.2294	0.2966	$MSE_{(Plot(trt))}/MSE_{(error)} =$	3.83	<.0001
Error	488	37.8176	0.0775			
Total	512	48.2112				
R^2	CV	Root MSE	Mean			
0.2156	99.3106	0.2784	0.2803			

Tukey's studentized range test was used for multiple comparisons to evaluate which treatments were significantly (α=0.05) different than one another (Table 2-11). The 'Uncut Control' was found to have a significantly smaller mean dbh increment (.17cm) than the '50m Strip' (.38cm) and '100m Strip' (.38cm) treatments. With visual analysis of the mean dbh increment values, one can see that '50m Strip' and '100m Strip' treatments show mean dbh increments almost double that of the average dbh increments experienced by the 'Mod Shelter' treatment, even though a significant (α=0.05) difference does not exist between them.

Table 2-11: Mean dbh increment for the fifth growing season following treatments

Treatment	Mean DBH Increment (cm)	Standard Deviation (cm)	N	Significance Grouping
'Uncut Control'	0.17	0.23	74	B
'Mod Shelter'	0.21	0.29	201	AB
'50m Strip'	0.38	0.34	139	A
'100m Strip'	0.38	0.28	99	A

Diameter Increment Response Analysis

Another measure of white spruce diameter growth release is diameter increment ratio. The diameter increment ratio is calculated in a similar manner as is used by Bella and Gal (1996) as seen in Equation 2-2 below.

Equation 2-2

$$Ratio = \frac{\left(Five\ year\ DBH\ increment_{After\ Treatment}\right)}{\left(Five\ year\ DBH\ increment_{Before\ Treatment}\right)}$$

In contrast, Bella and Gal (1996) used the mean annual diameter increment for the five years after treatment and divided it by the mean annual diameter increment for the five years before treatment. Equation 2-2 and the equation used by Bella and Gal (1996) result in the same ratios.

This ratio is derived from a sample of increment core measurements. This diameter increment ratio is used to provide a relative measure of residual white spruce tree diameter growth change following harvesting treatment. A ratio of one would indicate no change in diameter increment from the five years post-treatment to the five years pre-treatment. Treatment response should only be considered relative to the control ratio; i.e. the control ratio may not be equal to one due to variation in quality of growing seasons in the five years pre- versus the five years post-treatment. The diameter increment ratio is compared between treatments by way of ANOVA. The null hypothesis being tested is that there is no difference in mean diameter increment ratio between treatments.

The ANOVA test for the difference between diameter increment ratios is significant (α=0.05); therefore, the null hypothesis is rejected and we conclude that at least one of the harvest treatments results in a significantly different mean diameter increment ratio than another. Table 2-12 shows the ANOVA output.

Table 2-12: ANOVA table for comparison of mean diameter increment ratios between treatments

Source of Variation	Df	SSE	MSE	F	Pr>F
Model	3	5.6494	1.8831	8.06	<.0001
Error	114	26.6260	0.2336		
Total	117	32.2754			
R^2	CV	Root MSE	Ratio Mean		
0.1750	41.2674	0.4833	1.1711		

An HSD test is conducted for multiple comparisons and a number of significant (α=0.05) differences are identified (Table 2-13). The '50m Strip' treatment has the largest mean diameter increment ratio of 1.44, and is larger than the 'Mod Shelter' treatment and the 'Uncut Control' with ratios of 1.02 and 0.68, respectively. The '100m Strip' treatment has a diameter increment ratio of 1.18 that is significantly (α=0.05) larger than the 'Uncut Control' diameter increment ratio.

Table 2-13: Tukey groupings for diameter increment ratio

Treatment	Mean Ratio	N	Significance Grouping
'Uncut Control'	0.68	9	C
'Mod Shelter'	1.02	37	CB
'50m Strip'	1.44	36	A
'100m Strip'	1.18	36	AB

One can also visually assess the plot of diameter increment ratio versus an independent variable to identify potential patterns. A plot of interest is diameter increment ratio versus some estimate of the

reduction in competition factor. The competition factor that was chosen for this exercise is deciduous basal area greater than (BAGT – m^2/ha). BAGT is the sum of basal area for the deciduous trees taller than the subject tree. In order to evaluate the reduction in BAGT resulting from treatment activities, the assumption is that the 'Uncut Control' plots reflect the pre-treatment conditions. The post-treatment conditions can be evaluated for a subject tree (*i*) by calculating BAGT with the actual subject tree's plot data; i.e. this is the actual subject tree's competitive status at the time of measurement. The pre-treatment conditions can be evaluated for a subject tree (*i*) by calculating BAGT with the mean 'Uncut Control' plot data; i.e. the subject tree is evaluated as if the subject tree was located in the mean 'Uncut Control' plot. Thus, the basal area for the deciduous trees taller than the subject tree in the mean 'Uncut Control' plot are summed to calculate pre-treatment BAGT. For each subject tree (*i*) the pre-treatment competition factor is assessed ($BAGTCon_i$) and the post-treatment competition factor ($BAGTPlot_i$) is subtracted to estimate the reduction in competition factor ($\Delta BAGT_i$). Equation 2-3 depicts how ΔBAGT is calculated.

Equation 2-3 $$\Delta BAGT_i = [BAGTCon_i] - [BAGTPlot_i]$$

BAGT is assumed to be an aspatial competition factor, and ΔBAGT is considered to be an estimate of reduction in competition factor, and thus is a measure of individual tree release. A larger ΔBAGT means a greater level of overstory removal and thus, greater individual release. The diameter increment ratio represents individual tree response. Thus the plot of diameter increment ratio versus ΔBAGT depicts individual white spruce *response to release.*

Figure 2-2 shows the plot of diameter increment ratio versus ΔBAGT. The maximum response is observed in the highest range of ΔBAGT (27-31m^2/ha). The individual residual white spruce tree response is as high as 3.34. The trees that are responding with ratios greater than 2, are on average one metre shorter than the average white spruce trees sampled. In the ΔBAGT range greater than 7m^2/ha, we consistently see individual trees with ratios in the range of 0.5-2. A non-linear trend line is also included in Figure 2-2. This trend indicates that on an individual tree basis, with a greater ΔBAGT one can expect to see a greater mean increase in diameter increment.

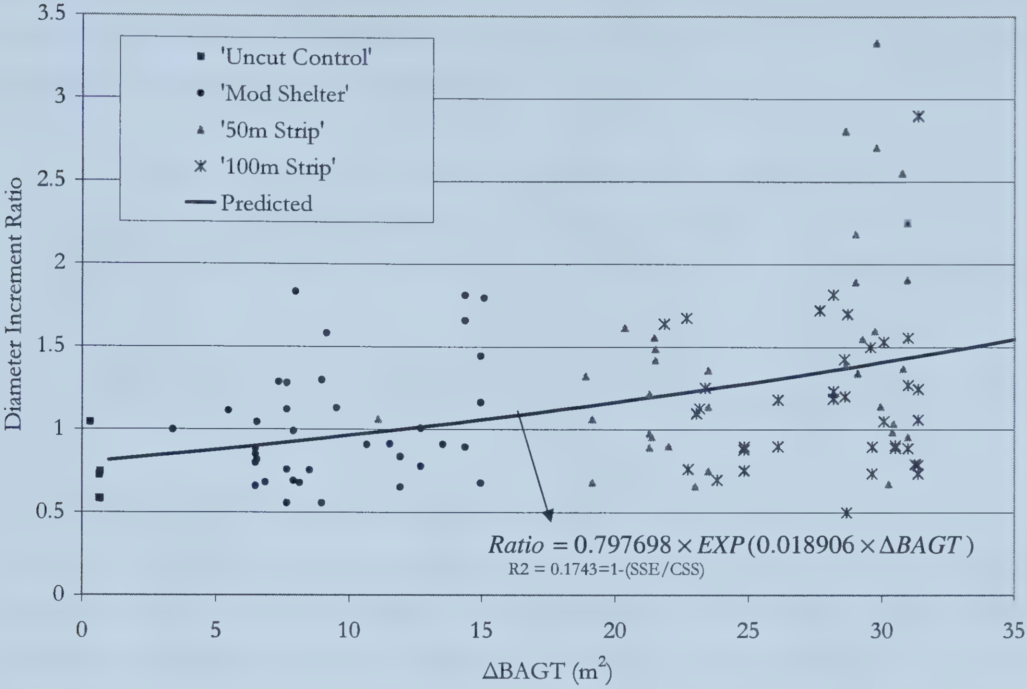

Figure 2-1: Diameter increment ratio vs. reduction in deciduous basal area greater than

There is a relatively clear division of ΔBAGT for treatments as a direct result of treatment design. In the 'Mod Shelter' treatment all residual white spruce trees occur in the ΔBAGT range of 3-15m²/ha. The '50m Strip' and '100m Strip' treatments occur in the ΔBAGT range of about 18 to 31m²/ha. The individual trees that show the superior response (ratios greater than 2) are in the ΔBAGT range of 27-31m²/ha; with 31% of the trees in this range displaying ratios greater than 2 (Table 2-14).

Table 2-14: Percentage of white spruce trees in various diameter increment ratio classes

Diameter Increment Ratio	'Uncut Control'	'Mod Shelter'	'50m Strip'	'100m Strip'
0 to .5	12.5	0	0	2.8
.5 to 1	75	59.5	28.6	38.9
1 to 1.5	12.5	27	37.1	36.1
1.5 to 2	0	13.5	17.1	19.4
2 to 2.5	0	0	5.7	0
2.5 to 3	0	0	8.6	2.8
Greater Than 3	0	0	2.9	0

The high ratio range of individual trees from the '50m Strip' treatment, perform better than individuals from the '100m Strip' treatment. The overall mean ratio for the '50m Strip' treatment is greater than the '100m Strip' treatment, 1.44 and 1.18, respectively. However, the majority of the individual trees in

the '50m Strip' and '100m Strip' treatments had a ratio in the same range as the 'Mod Shelter' treatment, between .5 and 2. Table 2-15 depicts the mean ending deciduous BAGT, the mean ΔBAGT, and the mean diameter increment ratio for each treatment.

Table 2-15: Mean BAGT and ratio characteristics for the various treatments

Treatment	Mean Post-Treatment BAGT (m^2/ha)	Mean ΔBAGT (m^2/ha)	Mean Diameter Increment Ratio
'Uncut Control'	31.17	0	.68
'Mod Shelter'	20.62	9.66	1.02
'50m Strip'	4.18	25.57	1.44
'100m Strip'	2.95	27.93	1.18

2.4 Stand Level White Spruce Analysis

Assessment of response on the individual tree basis can assist in a better understanding of how a released tree can react. Is it sufficient for one to conclude that because a harvesting treatment results in the most favourable individual tree response that it is the best treatment? Operationally, stand level characteristics such as density and stand volume must also be included in the response evaluation process. From an operational standpoint, it is more important to look at how the stand is responding. Density and volume per hectare are two fundamental measures of stand yield.

2.4.1 Residual White Spruce Density Distribution

Variation in density and its distribution can be attributed to a combination of factors. The change could be due to the mechanical manipulation of the stand in the way of treatment activates; it could be an aggregation of individual tree responses to the treatment in the way of altered growth and mortality; or it could be an artefact of the treatment area and the characteristics that pre-existed the treatment. In the short-term, as is being evaluated in this chapter, the most likely cause in variation between treatments of density would be as a direct result of the mechanical manipulation of the stand.

An ANOVA test was conducted to evaluate the white spruce densities in the various treatments. The null hypothesis being tested is that all treatments have the same white spruce density. Significance (α=0.05) is present between treatments resulting in the rejection of the null hypothesis; thus, concluding that at least one of the treatments has a significantly different white spruce density than another (Table 2-16).

Table 2-16: ANOVA test for mean density between treatments

Source of Variation	Df	SSE	MSE	F	Pr>F
Model	3	310620.6443	103540.2148	3.64	0.0293
Error	21	596919.8557	28424.7550		
Total	24	907540.5000			
R^2	CV	Root MSE	Ratio Mean		
0.342266	47.94666	168.5964	351.6333		

The HSD test shows that the 'Uncut Control' has a significantly (α=0.05) larger mean white spruce density than the '50m Strip' and '100m Strip' treatments, as shown in Table 2-17. The 'Uncut Control' area has more than twice the white spruce density compared to the '50m Strip' and '100m Strip' treatments. The 'Mod Shelter' treatment has an estimated mean density of 433.1 stems per hectare, which is not significantly different than the other treatments or the 'Uncut Control'. None of the three treatment densities were found to be significantly (α=0.05) different than one another, in spite of the apparent difference, with the 'Mod Shelter' treatment having larger densities then the '50m Strip' and '100m Strip' treatments.

Table 2-17: HSD groupings between treatments for density

Treatment	Density (stems/ha)	N	Significance Grouping
'Uncut Control'	633.3	2	A
'Mod Shelter'	433.1	8	AB
'50m Strip'	265.7	7	B
'100m Strip'	274.9	8	B

The mean white spruce density distribution by diameter class is summarized in Figure 2-2. The white spruce densities in the range greater than 9cm dbh are notably larger in the 'Uncut Control' than in the treatments. This is a direct result of harvest; i.e. the removal of these size trees during the two-stage tending and harvesting treatments. In treatment 'Mod Shelter' densities in the 14 to 20 cm diameter class range are greater than in the '50m Strip' and '100m Strip' treatments; this characteristic is an artefact of treatment design, as this treatment included the use of five metre wide buffers.

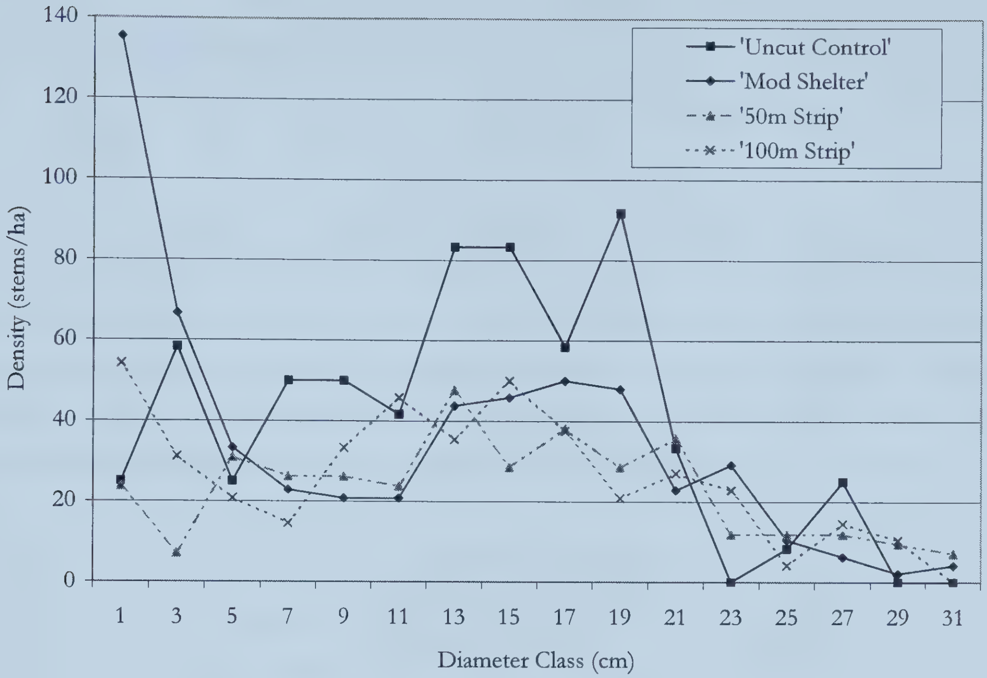

Figure 2-2: White spruce density distribution

Another thing to note about the white spruce densities in Figure 2-2 is the high density in treatment 'Mod Shelter' in the 1 cm diameter-class. This high density of young white spruce trees reflects stand conditions before treatment. This component of young white spruce trees will have a large impact on the softwood volume during the second round of harvesting in 60 to 80 years. Other distribution characteristics look similar between treatments.

2.4.2 Stand Level Volume Yield Analysis

Per hectare volume estimates are made for the various treatments with each individual plot. There are eight estimates for the 'Mod Shelter' and '100m Strip' treatments, there are seven estimates for the '50m Strip' treatment and two estimates for the 'Uncut Control'. First, the individual residual white spruce tree's heights are estimated using the height-dbh relationship derived in section Appendix III (Sw Height/DBH Model). Second, the local ecologically based volume estimates are made (Huang 1994). These estimates are then converted into per hectare estimates by way of expansion factor. This results in one estimate per plot. An ANOVA is used to test the null hypothesis that the white spruce volumes per hectare in the various treatments are the same. Significance (α=0.05) was found in the ANOVA test; therefore, the null hypothesis is rejected and we conclude that at least one treatment's mean white spruce volume is significantly different than another's (Table 2-18).

Table 2-18: ANOVA stand white spruce volume in 1998

Source of Variation	Df	SSE	MSE	F	Pr>F
Treatment	3	2800.4151	933.4717	3.40	0.0366
Error	21	5762.2924	274.3949		
Total	24	8562.7076			
R^2	CV	Root MSE	Mean		
0.3270	45.1375	16.5649	36.6987		

The 'Uncut Control' was found to be significantly (α=0.05) different than the '50m Strip' and '100m Strip' treatments (Table 2-19) with an estimated volume of 69.2 m³/ha and volumes of 35.81m³/ha, and 27.63 m³/ha for the '50m Strip' and '100m Strip' treatments, respectively. None of the three two-stage tending and harvesting treatments are significantly (α=0.05) different than one another.

Table 2-19: HSD grouping for white spruce volume

Treatment	Mean white spruce volume (m³/ha)	N	Significance Grouping
'Uncut Control'	69.20	2	A
'Mod Shelter'	38.42	8	AB
'50m Strip'	35.81	7	B
'100m Strip'	27.63	8	B

2.4.3 Stand Volume Increment

With the PSP data alone, volume increment cannot effectively be assessed; this is due to the small time frame (one growing season) between measurements, the natural stand variation and the associated measurement error. Another option is available to make a gross volume comparison with a five-year increment. The CFS transect sampling provides an immediate post-treatment estimate of standing volume. This sample and the PSPs are sampling the same treatments, however, they are based on completely different and independent sampling designs. The CFS transect-based white spruce volume estimates and the PSP estimates are presented in Table 2-20.

Table 2-20: Mean white spruce volume in 1993 and 1998

Treatment	CFS volume 1993 (m³/ha)		PSP Volume 1998 (m³/ha)	
	Mean	Standard Deviations	Mean	Standard Deviations
'Mod Shelter'	40.26	40.23	38.42	16.74
'50m Strip'	29.89	26.17	35.81	16.39
'100m Strip'	28.32	21.13	27.63	17.35

In some preliminary analysis it became apparent that the high variation in volume estimates would create difficulties in a comparison using both the CFS and PSP data. As one can see with the relatively high standard deviations in Table 2-20, the two independent samples do not share similar levels of variation. This precludes the combined statistical testing of these two samples. The CFS estimates of volume are based on many small plots, which contribute to the higher level of variation.

A simple assessment of the mean volumes per hectare show us that treatment 'Mod Shelter' has a greater volume than the '50m Strip' and '100m Strip' treatments. Of these treatments, the '50m Strip' is the only one that appears to show an increase in volume per hectare over time between the two independent samples.

2.5 Discussion

Individual Residual White Spruce Tree Response

In this chapter, three two-stage tending and harvesting treatments are evaluated, and compared, for early residual white spruce growth response. On an individual tree basis the 'Uncut Control' area has greater mean yield characteristic; however, the harvesting treatments show greater mean growth characteristics when considering radial growth of individual residual white spruce trees.

The 'Uncut Control', on average, has taller and larger diameter residual white spruce trees than the three treatments. This difference is expected, due to the nature of harvest. The 'Uncut Control' contains the segment of the white spruce cohort which was merchantable; the same segment that was removed, at least in part, in the treatments. However, the various two-stage tending and harvesting scenarios on average results in the same size trees. Neither height nor diameter were found to be significantly different between the three treatments. Immediately, following treatment very little difference exists in the mean residual white spruce tree size as the objectives for the various treatments are similar in this respect. Understory white spruce trees were left on site if they were not of merchantable size or if they were out of reach from the machine corridors; thus, in the short-term similar height and diameter yields are expected. As these residual trees exploit release conditions the expectation is that variation in treatment design may result in variation in residual white spruce tree diameter and height.

In the early stages of this long-term project, height and diameter increment evaluation is restricted to an annual increment, representing the growth in the fifth growing season following treatment. This limits the ability to test for and recognize potential differences due to the relatively small increment that is being measured. The height increment evaluation is especially difficult in this regard due to the associated measurement error. With the use of a clinometer a measurement error of plus or minus

2.5% can be expected (Morgan and Titus 1985). This error inherent in height measurement may have contributed to the lack of significance between height increments.

Diameter increment, on the other hand, was found to be significant. The 'Uncut Control' has a significantly smaller diameter increment than the '50m Strip' and '100m Strip' treatments, with the 'Uncut Control' having a mean diameter increment half that of '50m Strip' and '100m Strip'. One thing to note is the timing of this diameter increment measurement and its relationship to the concept of response 'lag time'. This measurement represents the fifth growing season following treatment, which roughly corresponds with documented response 'lag time' (Youngblood 1991). As has been documented by a number of authors (Donner and Running 1986, Youngblood 1991, Urban et al. 1994), some response time is required before the maximum increase in stem growth is reached after release conditions are introduced. Klinka et al. (1992) indicates that the response time likely corresponds with the time required for foliar adaptation to increased light. Typically, a discussion of thinning and partial release, where resulting growth and yield is paramount, includes the timing of release; for instance, in Alaska a mature white spruce stand was thinned and monitored for radial growth release (Youngblood 1991). Radial growth of the stem was found to be unaffected until the fourth year after treatment when it then increased 27% per year for the next six years. When the growing space becomes reoccupied, the accelerating growth rate will slow but growth still may remain at a level higher than that of pre-treatment.

In the '50m Strip' and '100m Strip' treatments virtually all of the merchantable overstory was removed, providing a relatively uniform release environment for all residual white spruce trees. Thus, any variation in diameter increment represents an individual trees reaction to the change in environment brought on by the treatment. Gillespie and Hooker (1986) made a list of potential factors influencing the difference in response between individual trees; these included the age of tree, length of suppression, competition, genotype, and root grafting. In contrast to the '50m Strip' and '100m Strip' treatments, the inclusion of aspen buffers in the 'Mod Shelter' treatment resulted in greater variation in the release environment for individual residual trees. For example, a white spruce tree left on site may not experience release conditions or may experience full release conditions based on its positioning in relation to the buffer strip. Therefore, tree response variation is not only due to individual characteristics but also the microenvironment surrounding that individual tree. When evaluating treatment response, the treatment effect is an average of the individual tree characteristics and the micro-scale environments. Micro-scale characteristics such as residual aspen densities and distance to windward buffering are expressed on average across the treatment, as spatial information was not collected. Residual white spruce density is one micro-scale characteristic, which is not expected to be a limiting factor to the growth and survival of individual residual white spruce trees; however, the

deciduous overstory density may have a significant influence. This influence is depicted in Figure 2-1, with diameter increment ratio plotted against the estimated reduction in deciduous basal area greater than (ΔBAGT).

The 'Uncut Control' increment ratio is smaller than that in the '50m Strip' treatment. Variation in response is greatest in the '50m Strip' treatment with a number of individual trees showing the highest level of release. Some of the individual trees that did not show response may have been in dense groupings or located under residual sections of the overstory. Bella and Gal (1996) hypothesized that a large portion of such variation in ratio was related to "tree status" and the competitive spatial arrangement of trees; thus, treatment pattern could play a large role in individual tree response. However, the treatment on the micro-scale is restricted by a "random" or "natural" placement or distribution of trees and the removal of overstory trees are not always in perfect relation to desired patterns. It is evident that with an increase in overstory removal (as can be quantified by ΔBAGT) the potential for individual release is increased. The mean response of the individual trees provides a nice indication as to the individual tree's potential; however, some indication as to what this response means at the stand level is required for a more operational evaluation.

Stand Level Response

Residual density is the primary reason for early variation in stand level yield between and within the harvesting treatments. The difference in density found between the 'Uncut Control' sample and the '50m Strip' and '100m Strip' harvesting treatments are likely a direct result of the harvesting activity and an indirect result of the moderate occurrence of mortality in residual trees following the harvest activities. As depicted in the density distributions (Figure 2-2), the main difference in the '50m Strip', '100m Strip' treatments and the 'Uncut Control' is in the mature diameter classes (dbh classes 9 nine centimetres and above). The 'Mod Shelter' treatment is observed to have a high density for the one centimetre diameter class. This elevated density could only be explained as unique preharvest conditions; it also shows the 'Mod Shelter' treatment's successful preservation of sub-breast height spruce understory trees. This class of white spruce trees should form a significant component in sixty to one hundred years when the stand is once again ready for harvest. Growth projections of all of the treatments and the control are made based on post-harvest conditions in Chapter 4.

With current measurements of PSP volume yield and increment are assessed at the stand level. Similar to density, volume yield was found to be significantly different between the 'Uncut Control' and the '50m Strip' and '100m Strip' treatments; this finding is assumed to be a direct result of harvesting activity and an indirect result of residual tree mortality. No significant difference was found between the three harvesting treatments. Volume increment did not show any significant difference between any of the treatment and the control. The high plot-to-plot variation and the short period, which the

increment was measuring, hampered the identification of true differences. Upon future re-measurement over a longer period of time this analysis should prove to be more constructive.

The high variation in residual retention in the treatments is in part due to harvest-operator's inexperience with this type of harvest. The first strips cut, in the treatments that had two passes, had a highly variable residual retention through out the strips. The second strips, in the two pass treatments, were reported to carry a higher and more consistent residual white spruce density (CFS personal communication). All of the sampling for this project occurred in the first pass strips. Density variation between plots within a treatment results in equally high variation in volume per hectare estimates. Thus making the evaluation of true volume yield differences between treatments difficult; similarly in the evaluation of growth. The short period between measurements, result in smaller differences being compared, which also make the identification of treatment growth differences difficult.

The large variation that can be created following treatment implementation and the early status of this project makes for differences that are difficult to detect. Future measures may yield more significant results. Some of the findings indicate there is a trade-off between individual tree maximum potential growth and survival. This thesis does not directly addressed volume lost to mortality. Mortality of residual trees following treatment may become the limiting factor to the success of a harvest pattern.

2.6 Conclusion

At this early stage following treatments there are only a few conclusions that can be made regarding the residual white spruce cohort.

- Individual white spruce trees do not show a significant difference in early height growth and yield. Any differences in height that may have been present as a result of treatment activities were overshadowed by the high rate of within treatment height variation.

- Individual white spruce trees show significant radial growth response to release. With a greater change in overstory (more overstory aspen removal) the greater the potential for response to release for individual trees. Ultimately, the introduction of the best release opportunities breeds the best occurrence of individual spruce diameter increment response.

- Two-stage tending and harvesting treatment activities will change the density of the white spruce component of the stand; assuming relatively uniform stand conditions, this density can be well controlled. This information lends to the longer-term growth projections and potential volume optimization. None of the treatment's volume or density were found to be significantly different than another.

Due to the high variation of the treatments, evaluation is difficult at such an early stage following treatment. Additional re-measurement will allow for statistically supported identification of any growth differences in the residual white spruce trees both at the individual tree level and at the stand level.

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Chapter 3

REGENERATION COHORT GROWTH & YIELD

3.1 Introduction

The regeneration of white spruce (*Picea glauca*) and trembling aspen (*Populus tremuloides*) following disturbance vary due to differing resource tolerances and establishment methods (Greene et al. 1999, Kobe and Coates 1997, Wright et al. 1998, Messier et al. 1999). Trembling aspen is a shade intolerant species and is fast at getting established, by suckering following a disturbance. White spruce is considered a shade tolerant species and is relatively slow at establishing a site, by seed germination following a disturbance. In the lower foothills boreal forest these staggered rates of development can create management challenges and opportunities.

Natural shade tolerance and establishment characteristics make the occurrence of a trembling aspen overstory, over a white spruce understory a common stand structure in the boreal forest. One timber management scenario that can be used on this type of stand is the two-stage tending and harvesting scenario. The first-stage of this scenario involves the removal of the trembling aspen overstory while protecting the white spruce understory. The second-stage comes sixty to one hundred years later when the same block is revisited and the protected residual cohort and the regeneration cohort, which filled in the excess growing space, following treatment, is harvested. The focus of this chapter is on the growth and yield of the regeneration cohort. This stand component is important, as it will likely represent a critical component of the total volume when it comes time for second-stage harvest.

Expectations are that the regeneration cohort is composed primarily of trembling aspen. This expectation is based on the establishment characteristics of this species. White spruce regeneration may also be present in this cohort. The presence of shade tolerant spruce trees would not be surprising due to the ample seed source in the treatment areas and the localized shade provided by residual trees, which would help to reduce the vigorous establishment of the shade intolerant species and thus, providing growing space for the more tolerant slower growing white spruce regeneration.

Four two-stage harvesting and tending treatments were carried out in 1993, all with different predefined harvesting patterns. Measurements were made in the fifth (1998) and sixth (1999) year following treatment. These measurements provide data on early regeneration cohort growth and yield. The questions that are addressed in this chapter are:

- Is there a significant difference in the deciduous or coniferous regeneration density (stems/ha) between the four treatments?

- Is there a significant difference in the deciduous or coniferous regeneration mean height (m) between the four treatments?
- Is there a significant difference in the deciduous or coniferous regeneration mean height increment (cm) between treatments?

3.2 Methods

3.2.1 Study Area and Harvesting Treatments

A research area was established in northwestern Alberta in the lower foothills region of the boreal forest (Rowe 1972). The typical pre-treatment stand structure consisted of a ninety-year-old trembling aspen dominant overstory and a sixty-year-old white spruce understory (MacIsaac et al. 1999). Four of the harvesting treatments established in 1993 include operational avoidance ('Clearcut'), two-pass 100 strip width, two-pass 50m strip width and one-pass uniform-modified shelterwood. These harvesting scenarios were initially designed with varying degrees of understory white spruce protection in mind.

Operational Avoidance ('Clearcut')

In the operational avoidance cut block, white spruce trees were protected without a predetermined pattern of protection. Ultimately, this treatment is a clear-cut with very few residual trees left in the block. No residual trees were captured in our sampling of this treatment. For a diagram and aerial photograph of the treatment see Appendix I (Treatment Summary).

Two-Pass Strip Cut ('100m Strip' & '50m Strip')

The treatment area is divided into strips running perpendicular to prevailing winds (strips run north/south). Half of each strip is harvested by running machine corridors up the strip at twenty metre intervals. The windward side of each strip was left unharvested and the other half was harvested in a repeated pattern of eight-metre machine corridor and a twelve metre residual strip. There is two treatments utilizing this pattern of harvest, one with the first pass strip being one hundred-metres wide ('100m Strip') and one with the first pass strip being fifty-metres wide ('50m Strip'). The windward leading half of the strip is scheduled for harvest in this same pattern five years after the first harvest. For a diagram and aerial photograph of the treatment see the Appendix I (Treatment Summary).

One-Pass Modified-Uniform Shelterwood ('Mod Shelter')

The one-pass uniform modified shelterwood ('Mod Shelter') has machine corridors spaced twenty-five metres centre to centre; resulting in approximately an eight metre wide machine corridor, a six metre wide understory protection area where all aspen and mature spruce are removed by a feller buncher reaching into the stand on either side of the machine corridors. Due to the limited reach of the machine corridors a five-metre buffer, where no trees are removed, is left between the two residual

strips. This buffer represents an estimated fifteen percent of the merchantable volume that will be left in the block (Navratil et al. 1994). This treatment has characteristics that provide the greatest amount of understory white spruce protection and with these same characteristics leaves the least amount of growing space for the recruitment of regeneration. For a diagram of the treatment see Appendix I (Treatment Summary).

3.2.2 Sampling and Measurement

In order to monitor the regeneration densities and growth rates in the above treatments a network of permanent sample plots (PSPs) were established in 1998. PSPs were utilized as they would be re-measured and thus, allow for the tracking of individual tree performance over time. The experiment included data collection in two areas: machine corridors, where all of the overstory and understory are removed and the residual strips, where the overstory was removed and the spruce understory was protected. In the residual strips ten by sixty metre plots were established for full measurement of all trees taller than 1.3 metres. A pair of two by two metre subplots were established within the main PSP for the measurement of all trees including trees shorter than 1.3 metres. Plots with an identical design were established in the machine corridors; however, in this area only the subplots were sampled. Measurements such as diameter at breast height, total height, root collar diameter, previous years height increment, and condition code were recorded. A re-measurement was made on the plots in 1999; one year following plot establishment. This chapter utilizes the subplot measurements exclusively. Sampling strategies and measurement techniques are outlined in detail in Appendix II (Sampling and Measurement).

3.2.3 Analysis

The following analysis addresses various hypothesis about the regeneration established following treatment activities. Concepts included in the analysis are: pseudoreplication, analysis of variance, blocking and Tukey studentized multiple comparisons.

Pseudoreplication

In order to perform statistical tests to evaluate the treatments for significant differences, replicates of the experimental units must be available. With large-scale experiments, true replication is often not possible due to the size of the experimental units and the cost to implement them. Pseudoreplication is an alternative. Two assumptions must be met in order to conduct valid statistical tests with pseudoreplication. The first assumption is that experimental units (harvesting blocks) are assumed to have started out exactly the same (Hurlbert 1984). The second assumption is that the selection of the experimental units for treatment is assumed to be random (Hurlbert 1984). It is known that the harvest blocks did not start out exactly the same; however, they were selected because they were sufficiently similar. The second assumption is satisfied as well, because any variation among harvesting blocks

(experimental units) will be random among the treatments. With this form of replication the plots become the experimental unit.

Analysis of Variance

Analysis of variance (ANOVA) is the primary statistical test used throughout this chapter. A number of assumptions must be satisfied in order to correctly use this test procedure. The first assumption is that the treatment effect and the environmental effects are additive. Another assumption is that the experimental errors are assumed to be random, independent and normally distributed about a zero mean (Steel et al. 1997, p158). When these assumptions are satisfied a group of means treatment characteristics can be tested for significance. The variable means being compared sufficiently meet these assumptions. Throughout this thesis an alpha (α) value of 0.05 was used to evaluate a test's significance. With this level of alpha the probability of committing a type I error is equal to five percent.

Blocking

The concept of blocking is used to differentiate variation between plots in residual strips and plots in the machine corridors. The use of blocking for analysis follows the way the treatments were sampled. Blocking is utilized here because the variation of regeneration characteristics within an area (i.e. machine corridors or residual strips) is expected to be less than the variation between them (Steel et al. 1997). The blocking factor is assumed to have a fixed effect on the model.

Multiple Comparison

The Tukey Studentized range test (HSD – honestly significant difference) was used as the standard method of multiple comparisons throughout this thesis. The HSD test makes pair-wise comparisons between treatments while controlling alpha inflation (Rosenberg 1990), to evaluate which treatments are significantly (α=0.05) different than one another.

3.3 Regeneration Densities

The cohort of trees that are being considered in this analysis include deciduous trees with a dbh less than three centimetres and conifer trees with a height shorter than fifty centimetres. These cut offs were chosen to roughly differentiate trees that are new since treatment from those trees that are residuals.

The deciduous regeneration density is composed of three species: trembling aspen, white birch (*Betula papyrifera*), and balsam poplar (*Populus balsamifera*). The trembling aspen was the dominant regeneration species accompanied by a considerable occurrence of balsam poplar. Conifer trees, primarily white spruce, also form an important component of the regeneration cohort. To a lesser extent jack pine

(*Pinus banksiana*) regeneration also contributes to the total conifer density. The density summary of all regeneration species in all treatments is given in Table 3-1.

Table 3-1: Density summary by species.

Treatment	Density (stems/hectare)						
	Aw	Bw	Pb	Total Hardwood	Pj	Sw	Total Softwood
'Clearcut'	36,167	0	3,000	39,167	333	1,833	2,166
'100m Strip'	13,696	0	6,413	20,109	0	2,065	2,065
'50m Strip'	14,224	0	3,017	17,241	0	1,293	1,293
'Mod Shelter'	9,722	278	1,667	11,667	0	833	833

Deciduous Regeneration Densities

An ANOVA test is used to test the null hypothesis that there is no difference in deciduous regeneration densities between treatments. Treatment was found to significantly (α=0.05) contribute to the differences in deciduous densities (Table 3-2). Therefore, the null hypothesis is rejected and we can conclude that the deciduous regeneration density in at least one of the treatments is different than that in another. From this test one can see that the blocking factor (i.e. residual strip versus machine corridors) does not significantly (α=0.05) contribute to the model.

Table 3-2: ANOVA table for density of deciduous regeneration.

Source of Variation	Df	SSE	MSE	F		Pr>F
Treatment	3	6675099018	2225033006	$MSE_{(trt)}/MSE_{(error)}$ =	9.70	<.0001
Blocking*	1	7945095	7945095	$MSE_{(block)}/MSE_{(error)}$ =	0.03	0.8528
Error	89	20423176844	229473897			
Total	93	28035106383				
R^2	CV	Root MSE	Mean			
0.2715	76.3512	15148.40	19840.43			

* Residual Strip versus Machine Corridor

By performing a multiple comparison HSD test (Table 3-3) it is shown that the 'Clearcut' treatment holds significantly greater stems per hectare of deciduous regeneration than do the other harvesting treatments. The 'Clearcut' treatment has an estimated regeneration density of 39,167 deciduous stems per hectare, which is nearly twice the next greatest mean density of 20,109 deciduous stems per hectare found in the '100m Strip' treatment. The '50m Strip' and 'Mod Shelter' treatments had regeneration densities of 17,241 and 11,667 deciduous stems per hectare respectively. The '100m Strip', '50m Strip'

and 'Mod Shelter' treatments were all not significantly (α=0.05) different when compared with the HSD test.

Table 3-3: HSD groupings for density of deciduous regeneration.

Treatment	Adjusted Mean Density (stems/hectare)	Number of Samples (Sub-Plots)	Significance Grouping
'Clearcut'	39,167	15	A
'100m Strip'	20,109	23	B
'50m Strip'	17,241	29	B
'Mod Shelter'	11,667	27	B

Coniferous Regeneration Densities

An ANOVA test is conducted to identify significant differences in coniferous regeneration densities between treatments. The null hypothesis being tested here is that there is no significant difference in mean conifer regeneration densities between the four treatments. The ANOVA table depicting the results of this test is presented in Table 3-4. The treatment effect and the blocking factor are not found to be significant (α=0.05). Therefore, the null hypothesis cannot be rejected and one can conclude that there is no significant (α=0.05) difference in the conifer regeneration density between treatments.

Table 3-4: ANOVA table for density of coniferous regeneration.

Source of Variation	Df	SSE	MSE	F		Pr>F
Treatment	3	24623514.76	8207838.25	$MSE_{(trt)}/MSE_{(error)}$ =	0.97	0.4093
Blocking*	1	721090.97	721090.97	$MSE_{(block)}/MSE_{(error)}$ =	0.09	0.7707
Error	89	751023037.0	8438461.1			
Total	93	778989361.7				
R^2	CV	Root MSE	Mean			
0.0359	195.0435	2904.903	1489.362			

* Residual Strip versus Machine Corridor

3.4 Regeneration Height

Height is used as an indirect measure of regeneration vigour. By evaluating the mean heights of deciduous and coniferous species one can assess which treatment has regenerated more vigorously. This assessment is a direct measure of yield (i.e. a 'snap shot' in time) and is a function of how quickly regeneration became established and how fast the regeneration is growing in height. Alternatively, height increment is evaluated as a measure of growth (i.e. a change in height over time). The increment

that was available for analysis in this chapter is the height growth between the fifth and sixth year following treatment.

3.4.1 Height Yield

The height of the regeneration can provide indication of how quickly it became established following treatment and the vigour (growth rate) that it is experiencing. The mean height of the regeneration cohort by species and treatment is summarized in Table 3-5.

Table 3-5: Mean height summary table.

Treatment	Height (m)						
	Aw	Bw	Pb	Mean Hardwood	Pj	Sw	Mean Softwood
'Clearcut'	1.31		1.21	1.30	0.35	0.18	0.21
'100m Strip'	1.35		1.79	1.49		0.13	0.13
'50m Strip'	1.20		1.42	1.23		0.19	0.19
'Mod Shelter'	1.14	1.87	1.42	1.19		0.17	0.17

Two ANOVA tests are used to check for significant differences in the mean heights between treatments. The first tested the null hypothesis that the mean height of deciduous regeneration was the same in the four harvesting treatments. The second tested the null hypothesis that the mean height of coniferous regeneration was the same in all of the harvesting treatments.

Deciduous Regeneration Height

The treatment was found to have a significant (α=0.05) effect on deciduous regeneration mean height (Table 3-6). Thus, one can reject the null hypothesis and conclude that the mean height of deciduous regeneration is significantly (α=0.05) different in one treatment than in another treatment. The blocking of plot location was not significant (α=0.05), as was found with the use of this blocking factor in the density ANOVAs.

Table 3-6: ANOVA table for the height of deciduous regeneration.

Source of Variation	Df	SSE	MSE	F		Pr>F
Treatment	3	90993.4999	30331.1666	$MSE_{(trt)}/MSE_{(error)}$ =	5.97	0.0005
Blocking*	1	1174.6421	1174.6421	$MSE_{(block)}/MSE_{(error)}$ =	0.23	0.6308
Error	741	3765997.698	5082.318			
Total	745	3856997.517				

R^2	CV	Root MSE	Mean
0.0236	54.2791	71.2904	131.3405

* Residual Strip versus Machine Corridor

An HSD test shows significant differences between the '100m Strip' treatment, and the '50m Strip' & 'Mod Shelter' treatments. The '100m Strip' treatment has a deciduous regeneration mean height of 1.49m and the '50m Strip' and 'Mod Shelter' treatments have smaller mean deciduous regeneration heights of 1.23m and 1.19m, respectively (Table 3-7). It is noted that there is a larger component of balsam poplar in the '100m Strip' treatment, which contributes to a higher mean height as seen in the species mean height break down in Table 3-5. The 'Clearcut' treatment is not significantly different than any of the other treatments and has a mean height of 1.30m for its deciduous regeneration cohort.

Table 3-7: HSD groupings for the height of deciduous regeneration.

Treatment	Mean Height (m)	Number of Samples (trees)	Significance Grouping
'Clearcut'	1.30	235	AB
'100m Strip'	1.49	185	A
'50m Strip'	1.23	200	B
'Mod Shelter'	1.19	126	B

Coniferous Regeneration Height

The second ANOVA preformed on mean height was for the conifer regeneration component. The ANOVA results are presented in Table 3-8. This test was not found to be significant (α=0.05), indicating that the null hypothesis cannot be rejected. Thus, no difference was found between mean conifer regeneration heights between treatments. As in the ANOVA tests for mean densities and mean deciduous regeneration heights the blocking factor is found to be insignificant (α=0.05).

Table 3-8: ANOVA table for the height of coniferous regeneration.

Source of Variation	Df	SSE	MSE	F		Pr>F
Treatment	3	570.1247	190.0416	$MSE_{(trt)}/MSE_{(error)}$ =	2.36	0.0819
Blocking*	1	115.6488	115.6488	$MSE_{(block)}/MSE_{(error)}$ =	1.44	0.2359
Error	51	4099.0807	80.3741			
Total	55	4777.7455				
R^2	CV	Root MSE	Mean			
0.1420	53.1550	8.9652	16.8661			

* Residual Strip versus Machine Corridor

3.4.2 Height Increment

In order to more directly assess the height growth of the regeneration cohort, a one-year height increment was measured. This measure provides a direct assessment of annual growth. The mean previous years height increment or the regeneration cohort is summarized in Table 3-9 by species for each treatment.

Table 3-9: Mean height increment summary table.

Treatment	Height Increment (cm)						
	Aw	Bw	Pb	Mean Hardwood	Pj	Sw	Mean Softwood
'Clearcut'	34.1		19.4	33.0	14.0	7.1	8.2
'100m Strip'	39.9		25.4	35.7		3.5	3.5
'50m Strip'	35.4		23.6	33.3		6.7	6.7
'Mod Shelter'	27.4	49.0	19.7	26.8		3.9	3.9

Two ANOVA tests are used for comparison of this measure between treatments. The first null hypothesis is that there is no significant (α=0.05) difference between mean height increments of deciduous regeneration between treatments. The second null hypothesis is that there is no significant (α=0.05) difference in mean height increment of coniferous regeneration between treatments.

Deciduous Regeneration Height Increment

The average height increment of deciduous regeneration was found to be significantly (α=0.05) different in at least two of the treatments (Table 3-10). Thus, the null hypothesis must be rejected and can conclude that at least two of the treatments have a significantly (α=0.05) different mean deciduous regeneration height increment. The blocking factor (i.e. residual strip versus machine corridors) was not found to be significant (α=0.05).

Table 3-10: ANOVA table for the height increment of deciduous regeneration.

Source of Variation	Df	SSE	MSE	F		Pr>F
Treatment	3	5981.7251	1993.9084	$MSE_{(trt)}/MSE_{(error)}$ =	3.83	0.0097
Blocking*	1	0.9498	0.9498	$MSE_{(block)}/MSE_{(error)}$ =	0.00	0.9659
Error	724	376967.7995	520.6738			
Total	728	382987.1653				
R^2	CV	Root MSE	Mean			
0.0157	69.8489	22.8183	32.6680			

* Residual Strip versus Machine Corridor

A multiple comparison of the mean height increments is made by way of an HSD test. The '100m Strip' and '50m Strip' treatments were found to have significantly greater average height increments than the 'Mod Shelter' treatment. For the 'Clearcut' treatment the mean height increment for deciduous regeneration is not significantly different than any of the other treatments. The values of average height increments for the deciduous regeneration cohort are in Table 3-11.

Table 3-11: HSD groupings for the height increment of deciduous regeneration.

Treatment	Mean Height Increment (cm)	Number of Samples (trees)	Significance Grouping
'Clearcut'	33.0	232	AB
'100m Strip'	35.7	173	A
'50m Strip'	33.3	200	A
'Mod Shelter'	26.8	124	B

Coniferous Regeneration Height Increment

The ANOVA test for the mean height increment of conifer regeneration is found to be significant (α=0.05); thus, the null hypothesis must be rejected and we can conclude that at least two of the treatment's mean height increments for conifer regeneration are significantly different. The ANOVA results for this test are in Table 3-12. As with all of the previous ANOVA tests in this thesis, the blocking factor was found to be insignificant (α=0.05).

Table 3-12: ANOVA table for the height increment of conifer regeneration.

Source of Variation	Df	SSE	MSE	F		Pr>F
Treatment	3	218.3318	72.7773	$MSE_{(trt)}/MSE_{(error)}$ =	11.70	<.0001
Blocking*	1	16.6454	16.6454	$MSE_{(block)}/MSE_{(error)}$ =	2.68	0.1083
Error	48	298.4460	6.2176			
Total	52	518.5755				
R^2	CV	Root MSE	Mean			
0.4245	44.2735	2.4935	5.6321			

* Residual Strip versus Machine Corridor

An HSD test was conducted (Table 3-13); the 'Clearcut' and '50m Strip' treatments were found to be significantly (α=0.05) larger than the '100m Strip' and 'Mod Shelter' treatments. The conifer regeneration in the 'Clearcut' and '50m Strip' treatments had an average height increment of 8.2cm and 6.7cm, respectively, which is close to twice the average height increments observed for the '100m Strip' and 'Mod Shelter' treatments (3.5 and 3.9, respectively).

Table 3-13: HSD groupings for the height increment of conifer regeneration.

Treatment	Mean Height Increment (cm)	Number of Samples (trees)	Significance Grouping
'Clearcut'	8.2	13	A
'100m Strip'	3.5	16	B
'50m Strip'	6.7	15	A
'Mod Shelter'	3.9	9	B

3.5 Discussion

The treatments that were selected for this study provide a gradient of residual white spruce protection. The same characteristics, which provide residual tree protection, also create a gradient of growing space available to the regeneration cohort; one end of the gradient with full overstory removal and the other end with no overstory removal. The 'Clearcut' treatment has no residual tree retention and thus provides the most extreme overstory removal. The '50m Strip' and '100m Strip' treatments are somewhere in the middle along the gradient of available growing space with some overstory trees left on site and the residual white spruce trees that were protected. The 'Mod Shelter' treatment, representing more residual tree protection, is near the other end of the gradient, providing the least amount of excess growing space. The 'Mod Shelter' treatment includes extensive aspen buffering and the residual white spruce trees. A trade off occurs in this regard as such a treatment provides excellent wind protection to the residual white spruce trees where the regeneration cohort is not recruited as aggressively as in the 'Clearcut' treatment. The extreme end of the gradient would be an 'Uncut Control' block, which displayed no regeneration as a reflection of very little available growing space. Regeneration densities, height yields and height increments were compared between treatments along this gradient to evaluate where significant differences existed.

Regeneration Density

As would be expected in the lower foothills region the predominant species that established following harvest treatment was trembling aspen, with components of balsam poplar (Bella et al. 1996). Variation in the amount of poplar versus aspen regeneration that is observed between treatments appears to be directly related to the pre-harvest overstory makeup. Thus, when a treatment area starts out with a larger component of poplar it can be expected to regenerate an equivalently larger component of poplar. A number of white spruce trees also recruited in the treatment areas, along with a moderate occurrence of jack pine (*Pinus banksiana*) and white birch. Aspen and poplar are colonizing species following disturbance, such as the treatments provide (Greene et al. 1999). Aspen and poplar will sucker from the pre-existing root system when the overstory is removed; a hormone process in the roots drives this activity. In contrast, white spruce is a slower establishing species with regeneration

originating from seed germination (Greene et al. 1999), either from pre-disturbance seed source or from a seed tree. Many seed trees were available for the seeding of white spruce in these treatments, as protecting the understory white spruce trees, many of which were mature enough to act as a seed source, was an objective of the treatments.

The 'Clearcut' treatment was found to have the greatest regeneration density. This treatment was found to have significantly more deciduous regeneration than the other treatments. This is associated with the growing space available to the regeneration cohort. The 'Clearcut' treatment maximizes this growing space as virtually all of the overstory and understory trees are removed during harvest. In contrast to this, in the '50m Strip' and '100m Strip' treatments, some overstory aspen are retained in the block along with the white spruce trees left as residuals in the residual strips. By looking at the density of the residual cohort some indication of density of the regeneration cohort may be evident. The '50m Strip' and '100m Strip' treatments have an estimated density of aspen retention of 113 stems per hectare and 89 stems per hectare, and a white spruce residual density estimate of 240 stems per hectare and 206 stems per hectare respectively. While these densities do not provide crown closure conditions they can contribute to the reduction in available growing space for the recruitment of trees. Thus, regeneration densities are less in these treatments than in the clear-cut treatment. Similarly, the 'Mod Shelter' treatment has residual and overstory densities that reduce the available growing space. This treatment has an even greater estimated aspen retention and residual white spruce density of 411 stems per hectare and 440 stems per hectare, respectively. Although, these residual cohort densities appear to be a lot more than those for the '50m Strip' and '100m Strip' treatments, no significant difference was found in deciduous or conifer regeneration cohort densities between these treatments. The large variations observed may contribute to the insignificance. One reason large variations are observed is due to the small subplot size used for this analysis. However, this size of plot was the largest feasible provided the large number of small seedlings and suckers. With a larger plot the threat of measurement error in the form of missed stems would have been inflated.

Blocking by plot location was used throughout the analysis. This blocking was found in all cases to be an insignificant factor. This could be attributed to a flaw in the treatment sampling design. The potential problem is regarding the PSP size and the location of the subplots within the PSP. The PSPs are rectangular ten-metre by sixty-metre plots with subplots (two metre by two metre) in the southwest and northeast corners of the PSPs. Due to the treatments being strip treatments, where the PSP would often just fit in the strip the subplots were always located at the margin between the machine corridors and residual strips. This would occur whether it was a machine corridor PSP or a residual strip PSP and would often result in subplots for machine corridors being directly adjacent to subplots for the residual strips. By this design the difference between the subplots were not being maximized. Thus,

the variation within a plot location (i.e. machine corridors or residual strips) was not significantly less than the variation between plot locations (i.e. blocking by plot location was insignificant). Perhaps, a better differentiation could have been accomplished by locating the subplots in the middle of the strips.

Though there appears to be great early disparity in the mean deciduous density between treatments, it is of even more interest to see how this relates into deciduous density and volume in time for the next pass of harvest. Due to the nature of deciduous recruitment and regeneration maybe these large differences following treatment activates will not relate to significant differences sixty to eighty years from now. Such questions are addressed in Chapter 4.

Regeneration Height and Height Increment

Height is an indication of vigour for the regeneration cohort. In comparing average regeneration height between treatments it is found that the '100m Strip' treatment has a significantly greater mean height (1.49m) for the deciduous regeneration than does the '50m Strip' and 'Mod Shelter' treatments (1.23m and 1.19m, respectively). The 'Clearcut' treatment has a mean deciduous regeneration height of 1.30m, which is not significantly different than the rest of the treatments. Similarly, the '100m Strip' treatment's mean height increment of 35.7cm for deciduous regeneration is significantly larger than the 'Mod Shelter' treatment's height increment of 26.8cm. The '50m Strip' treatment also has a significantly bigger height increment than the 'Mod Shelter' treatment with a mean height increment of 33.3cm. The 'Clearcut' treatment, as with mean total height, is not significantly different than any of the other treatments when comparing mean height increment for deciduous species.

The effect of the high level of residual cohort density is being observed in the deciduous regeneration cohort. With shorter mean heights and slower average height growth rates, the productivity of this cohort appears to be reduced due to residual tree densities. At the other end of the available growing space gradient, in the 'Clearcut' treatment, one finds average heights that are not significantly different than any of the other treatments. With the high density of deciduous regeneration in the 'Clearcut' treatment the weaker trees are being weeded out as the cohort grows. Thus the ones that fall behind in height growth will no longer compete for the limited light resource and will eventually die out of the stand. At this early stage following disturbance the individual trees, which do not contain the competitive edge, that suckered following treatment with the stronger trees, are still alive but falling behind. As this treatment has a higher density it has a higher occurrence of these trees; thus, a higher variation in total height and annual height increment. This makes differentiating this treatment from the other treatments more difficult. In contrast the '100m Strip' treatment contains some residual trees, which may provide enough recruitment control to reduce over competition within the regeneration cohort, but does not contain too dense a residual cohort to impede the growth of the regeneration.

3.6 Conclusion

In the early stages following treatment, regeneration can be quite vigorous with high densities of deciduous trees competing to get established in the excess growing space. The following conclusions can be drawn regarding the regeneration cohort following these four two-stage harvesting and tending treatments.

- The early mean density of deciduous regeneration is inversely related to the amount of residual tree retention. With the 'Clearcut' treatment showing a significantly larger deciduous regeneration density then the other two-stage tending and harvesting treatments.
- Early coniferous density was not found to be significantly different between treatments. Treatment activates have no measurable effect on the density of conifer regeneration.
- The mean height and the mean height increment appear to be inversely related to the level of residual tree retention; i.e. more overstory trees retained less vigorous regeneration growth. The 'Mod Shelter' treatment, which had the greatest level of overstory retention, had smaller deciduous mean height and mean increment characteristics than the other treatments. The 'Clearcut' treatment was an exception, as it's mean deciduous height and height increment appeared to be in the middle of the other treatments and was not significantly different than any of the other treatments.
- The difference in regeneration characteristics between the machine corridors and the residual strips is inconclusive due to a design flaw, which saw the subplots located along the edges of the respective areas.

Evaluation is difficult at such an early stage following treatment. With the use of projections or additional remeasurement, conclusions can be solidified.

3.7 Literature Cited

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Chapter 4

POST-TREATMENT STAND PROJECTION

4.1 Introduction

Stand attribute modeling is valuable to the forest industry, as it provides estimates of what characteristics a stand has today and what characteristics a stand will have in the future. Estimation of future conditions is typically based on the existing stand attributes and past experience with how they change over time. There are many ways to perform projections of stand characteristics; from simple stand level volume age relationships, as would be observed in a yield curve, to the projection of individual tree characteristics based on their position relative to other trees. There are numerous models used extensively for projection of forest stands. The Mixedwood Growth Model (MGM) is one such model.

MGM is a deterministic individual-tree-based growth model (Titus 2002). It was developed with focus on four primary species: trembling aspen (*Populus tremuloides*), white spruce (*Picea glauca*), jack pine (*Pinus banksiana*) and black spruce (*Picea mariana*). MGM is distant independent and therefore is an a-spatial model, which assumes a random spatial distribution of trees. This is the model used to make projection for this study.

One type of forest projection that is of particular interest is the projection of stands following silviculture treatment. Knowing what to expect following a silviculture treatment is important in forest management decision-making, providing a basis of economic evaluation of the treatment today. With estimates of future conditions following treatments one can evaluate if investment in a treatment will result in net gains. Long-term growth information on specific silviculture treatments is not available and is hard to acquire because treatments that are of interest today may not be the treatments that are of interest tomorrow, precluding long-term (100 plus years) sampling in a given treatment. It is expected that models such as MGM, which were not developed with empirical treatment data, should still be able to give reasonable treatment projections because of the underlying growth and mortality functions. Some early measurements of treatments can be used as the basis for projection.

The silviculture treatment explored is the two-stage tending and harvesting system (Brace and Bella 1988). This treatment involves two stages; one to remove the overstory while protecting the understory and a second, 60 to 80 years following the first-stage, to remove the residual trees and any new regeneration. These treatments are carried out in mixed trembling aspen and white spruce stands, where the overstory aspen are removed in the first-stage and the understory spruce is protected until

harvest in the second-stage. There are four two-stage tending treatments and one 'Uncut Control' that are projected for comparison.

The purpose of this chapter is two-fold. The first objective is to project the various treatments with MGM using the measured five years post treatment as the starting conditions. These projections will then be compared between treatments to identify differences in volume and density characteristics. The second objective is to evaluate a simulation of a typical two-stage harvesting scenario. This evaluation will be in the form of a general discussion on the assumptions of MGM and how they contribute to the modeling of this treatment scenario.

4.2 Methods

4.2.1 Two-Stage Tending and Harvesting Treatments

There are four treatments, and an 'Uncut Control' that were all projected with MGM. The treatments used here are a one-pass uniform modified shelterwood ('Mod Shelter'), two two-pass alternating strip cuts ('50m Strip' & '100m Strip'), and a 'Clearcut' treatment. The details of these treatments are outlined in Appendix I (Treatment Summary) and by Navratil et al. (1994).

4.2.2 Mixedwood Growth Model Projections

MGM is continually under improvement, as new data is available and new modeling ideas are developed, so it is important to make note of which version is being used for the projections in this exercise. The MGM version dated May 30, 2002 is used for this study.

The MGM projections are governed by the existing height increment model, the diameter increment model and the mortality model. The height increment model uses site index to help define the maximum height increment. A proportional reduction of height increment is made to account for competition. This reduction factor increases as crowding increases and light decreases. Crowding and light conditions are determined with basal area per hectare of trees with a larger dbh then the diameter class of trees being considered (Titus 2002). The height increment model is not applied to juvenile height growth, rather only those trees with a dbh greater than four centimetres. Juvenile height increment is based on a separate and more simplified function.

The diameter increment model in MGM assumes that diameter increment is proportional to the predicted height increment. Basal area per hectare of larger dbh trees and a spacing factor are used to derive the proportion. Diameter increment decreases when basal area in larger trees increases and/or when the spacing factor decreases. Conversely, diameter increment increases when basal area in larger trees decreases and/or when the spacing factor increases. To prevent excessive diameter increments in very widely spaced stands there is a restriction in place on the spacing factor. This diameter increment

model does not reflect juvenile diameter growth, rather only those trees with a dbh greater than 4.0 centimetres. The diameter increment for juvenile trees is based on a different, more simplified, function.

In MGM a mortality function is used that is based on a probability of survival. The probability of survival is modeled as a function of diameter at breast height, diameter increment, total basal area per hectare, basal area per hectare of trees with larger dbh than the subject tree, and species association based on proportion of basal area. In a number of cases accelerated mortality is triggered by a number of factors. A maximum size density limit is used as a trigger for accelerated mortality. A maximum biological threshold mean stand height is defined in relation to natural stand break up and is used as a trigger for accelerated mortality. Finally, a maximum basal area per hectare is defined by species and is used as a trigger for accelerated mortality. Juvenile mortality rates can also see higher rates when associated with extreme densities. Lower survivorship is observed when densities exceed 10,000 stems/ha.

There are a number of model options that were used for all of the MGM runs in this chapter. The Alberta Lower Foothills variant was used as the treatments were carried out in this natural subregion. The treatments were considered to be on a medium site and thus a site index for trembling aspen was considered to be 16 and the site index for white spruce and jack pine were considered to be 14. The ingrowth function was off and there was no reduction in total volume for merchantability. All settings can be seen in the crop plans in Appendix VI (MGM Crop Plans).

There is an important assumption, which MGM is based, that does not hold true for the purpose of our treatments. MGM is an a-spatial model and thus assumes that the spatial distribution of trees is random. The treatments that are of interest are pattern-based strip-cuts that do not have a stand wide random distribution of trees. There are two options for the projection of such stand conditions. The first option would be to grow the residual strips and the machine corridors separately. In this scenario MGM would model the two sections of the stand as if they were unrelated to one another. The drawback to this is that you do not get any of the edge effect that would be seen in the machine corridors by being next to the residual strips and visa versa, the residual strips being next to the machine corridors. The second option is to average the stand conditions of the machine corridors and the residual strips across the stand, weighted by area. This would mean that MGM would grow the stand as if evenly and randomly distributed. This was the approach taken for this exercise.

4.3 MGM Simulation of post-treatment growth

MGM was used to generate projected densities and volumes. Mean diameter distributions are derived for each residual strip plot and machine corridor plot combination, providing a treatment wide per hectare tree list for each plot combination in each treatment. The final distributions were to one-centimetre diameter classes. The number of resulting tree entries for each plot is summarized in Appendix VI (MGM Crop Plans) in Table A-3. It is worthy to note that there are relatively few entries in the plot based tree lists, especially in the 'Clearcut treatment tree lists (with 2-4 entries per plot). With a larger number of unique entries, more detail on the specific within plot variation would be included in the lists. With more detail on the true stand variation it is expected that MGM would be able to better model the stands characteristics.

The tree lists were used as input into MGM and were projected 70 years to assess the projected future volume and density. This provided a number of projection observations for each treatment. The mean projection for each treatment is used for graphical comparison. The associated crop plans are in Appendix VI (MGM Crop Plans).

4.3.1 Projected Conifer Densities

The means of conifer densities, as provided to MGM for modeling, are those densities at five years following harvest in Figure 4-1. As is apparent, there is a large range of starting densities between treatments from 2,868 stems per hectare in the '50m Strip' treatment to as low as 658 stems per hectare in the 'Uncut Control'. These densities include all sizes of conifer trees. It is worthy to note that the values depicted in Figure 4-1 represent the mean conifer densities for each treatment; i.e. the mean of all of the individual plot projections for each treatment.

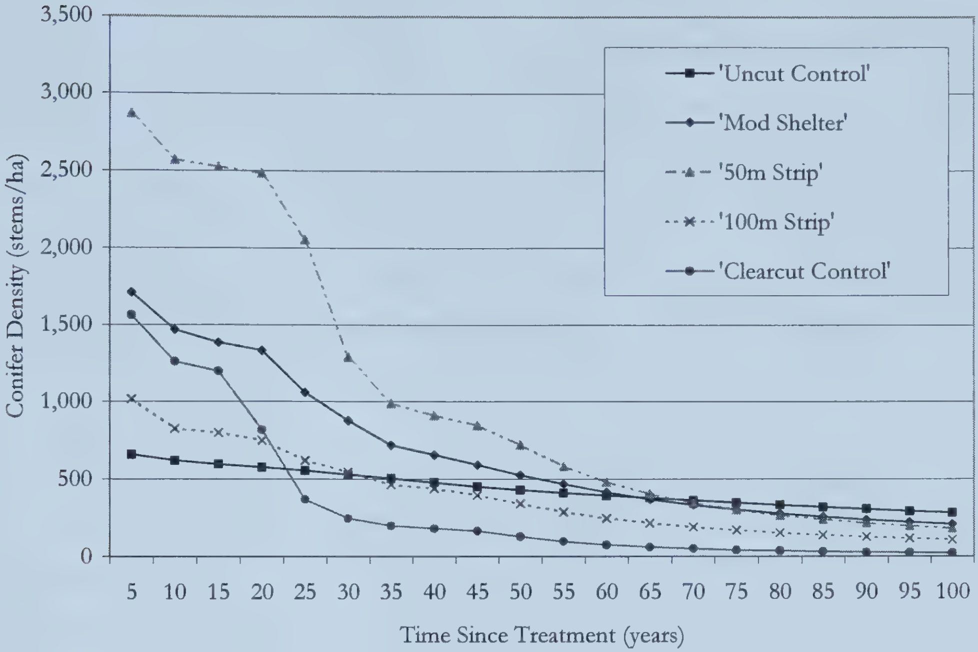

Figure 4-1: Treatment average conifer density projections

In Figure 4-1, the wide variability in conifer density between treatments narrows as the stand is modeled by MGM. A mortality function in MGM tends to reduce densities in the higher density stands more rapidly. This compared to the 'Uncut Control' that started out with a reasonable conifer density for a mature stand and remained relatively stable with a steady mortality influence throughout the modeling time frame. Projected conifer densities ended up within a much more narrow range then the starting conditions.

The mean projected conifer densities at year 70 for the treatments and the 'Uncut Control' are shown in Table 4-1. There appears to be large differences in the mean densities between treatments. These observations are also accompanied by high variation.

Table 4-1: Mean projected conifer densities.

Treatment	Mean Conifer Density (stems/ha)	Standard Deviation (stems/ha)	Number of Samples (plots)
'Clearcut'	50.02	73.50	8
'100m Strip'	188.21	127.73	8
'50m Strip'	345.58	378.87	8
'Mod Shelter'	332.58	281.19	8
'Uncut Control'	362.55	30.26	2

4.3.2 Projected Deciduous Densities

Similar to the starting conifer densities, there is a wide range of starting deciduous densities between the treatments and the 'Uncut Control'. As seen in Figure 4-2, five years following treatment the 'Clearcut' treatment has the largest deciduous density of 40,156 stems per hectare and the 'Uncut Control' as the lowest deciduous density of 758 stems per hectare. This discrepancy in density reflects the heavy recruitment of new trees in the treatments versus the mature stand conditions in the 'Uncut control' area. The majority of the deciduous densities in the treatment areas are shorter than 1.3 metres in height. With such high deciduous densities in the treatment areas, one would expect high mortality resulting in projected reductions in densities. This is reflected in the MGM projections.

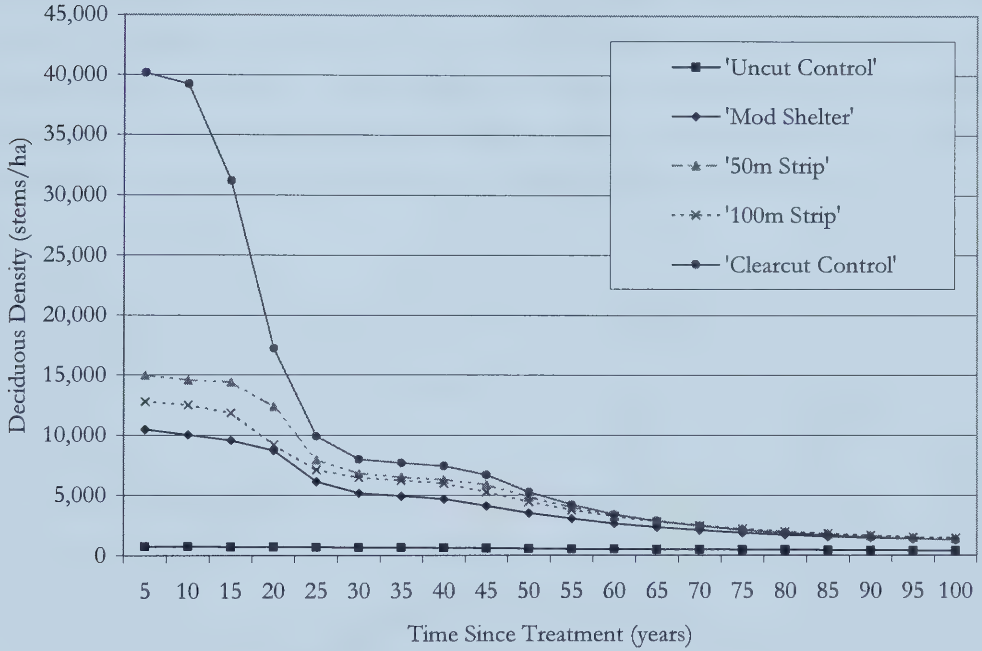

Figure 4-2: Treatment average deciduous density projections

The mean projected deciduous density at year 70 of the 'Uncut Control' appears to be different than all of the four treatments (Table 4-2). All four of the treatment areas have relatively high projected densities ranging from 2,074 stems per hectare ('Mod Shelter') to 2,474 stems per hectare ('100m Strips') compared to the projected deciduous density in the 'Uncut Control' of 492 stems per hectare. There also appears to be a relatively clear division of projected deciduous density between the 'Mod Shelter' treatment and the three other treatments, with the 'Mod Shelter' treatment sporting a projected deciduous density around 400 stems per hectare less than the other treatments.

Table 4-2: Mean projected deciduous densities

Treatment	Mean Deciduous Density (stems/ha)	Standard Deviation (stems/ha)	Number of Samples (plots)
'Clearcut'	2405.61	196.15	8
'100m Strip'	2462.15	208.88	8
'50m Strip'	2474.33	271.12	8
'Mod Shelter'	2074.33	382.58	8
'Uncut Control'	492.11	40.45	2

4.3.3 Projected Conifer Volumes

The 'Uncut Control' starts out with a conifer volume of 85.82 m^3/ha, five years following treatment. The 'Mod Shelter', '50m Strip' and '100m Strip' treatments have starting conifer volumes of 37.16 m^3/ha, 31.91 m^3/ha and 24.91 m^3/ha, respectively. The 'Clearcut' treatment, with no mature conifer trees, had a starting conifer volume of 0 m^3/ha. MGM projected the stands to increase in conifer volume as seen in Figure 4-3. The 'Mod Shelter', '50m Strip' and '100m Strip' treatments all stopped increasing in volume at 45 years following treatment. This is an important point as it may make an earlier second-stage harvest more viable if the objective is to maximize conifer volume.

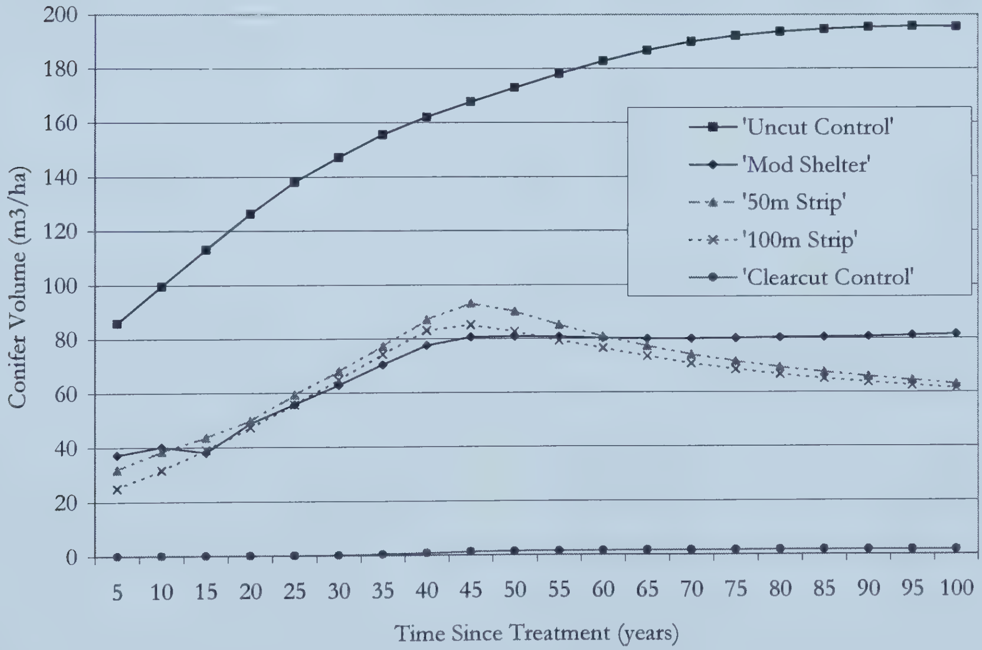

Figure 4-3: Treatment average conifer volume projections

The 'Uncut Control' has a larger mean conifer volume than the rest of the treatments. The 'Clearcut' treatment has a smaller mean conifer volume then the rest of the treatments. None of the rest of the

treatments appears to have very different mean conifer volumes than one another. The mean projected conifer volumes are presented in Table 4-3.

Table 4-3: Mean projected conifer volume.

Treatment	Mean Conifer Volume (m^3/ha)	Standard Deviation (m^3/ha)	Number of Samples (plots)
'Clearcut'	1.64	2.77	8
'100m Strip'	70.63	40.44	8
'50m Strip'	73.92	32.60	8
'Mod Shelter'	79.80	50.02	8
'Uncut Control'	189.95	16.40	2

4.3.4 Projected Deciduous Volumes

In the treatment areas the majority of the deciduous volume has been removed as a function of the treatment. This is reflected in the initial starting deciduous volumes. The 'Mod Shelter' treatment includes aspen buffers as part of the treatment and this is depicted in the higher deciduous volume relative to the other treatments, as seen in Figure 4-4. All treatment projections show increasing deciduous volumes throughout the length of the projection. A levelling of the rate of deciduous volume increase is observed at 45 years following treatment. This point is of particular interest as it is where the stand basal area limit is met.

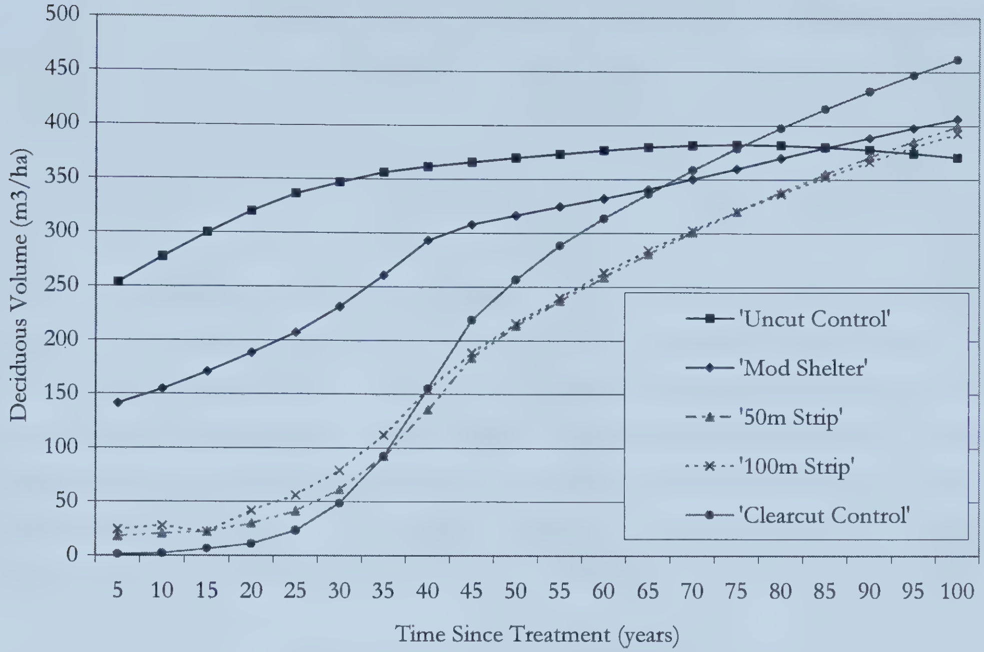

Figure 4-4: Treatment average deciduous volume projections

The mean projected deciduous volumes are presented in Table 4-4. The '50m Strip' and '100m Strip' treatments have smaller mean projected deciduous volumes then the 'Clearcut' and the 'Uncut Control', with a projected deciduous volume of around 300m³/ha as compared to a projected deciduous volume of around 350m³/ha.

Table 4-4: Mean projected deciduous volume.

Treatment	Mean Deciduous Volume (m³/ha)	Standard Deviation (m³/ha)	Number of Samples (plots)
'Clearcut'	358.32	18.12	8
'100m Strip'	302.29	29.40	8
'50m Strip'	300.73	25.70	8
'Mod Shelter'	350.13	28.95	8
'Uncut Control'	381.49	3.54	2

4.4 MGM Simulation of a Typical Two-Stage Harvesting Scenario

The full simulation of a two-stage tending and harvesting treatment is also conducted in MGM. This requires a number of assumptions and inputs to establish an initial stand the recruitment of an understory, the levels of tree removal during treatment and the subsequent recruitment of trees

following treatment. All of these assumptions were made to emulate a two–stage tending and harvesting treatment in the middle of the four that are examined earlier in this chapter. In order to make this projection, MGM must use a number of 'grow', 'regen', and 'thin' events to string together a simulation. The full MGM crop plan, used for this simulation, is in Appendix VI (MGM Crop Plans). The resulting MGM output provides a look at the stand characteristics (volume and density) over time from the establishment of the original stand through the first harvest and to the potential second harvest.

4.4.1 The Two-Stage Forestry Crop Plan

Within the events that MGM has to select from, one can establish a stand, project the stand characteristics over time, remove components of the stand by way of thinning events, add additional trees to the stand, and continue to project the stand characteristics. With these events one should be able to simulate the two-stage tending and harvesting treatment and evaluate predicted outcomes. The general steps outlined in Table 4-5 were utilized to conduct a full treatment simulation in MGM. The details of these steps and the actual crop plan used are available in Appendix VI (MGM Crop Plans).

Table 4-5: Full Simulation Crop Plan Description

Stand Age	Description
10	Establish main canopy (Aw, Pb, and Pj)
…	*Grow*
20	Establish main canopy (Sw)
…	*Grow*
50	Add understory layer (Sw)
…	*Grow*
90	First-stage harvest as defined by a series of thin events
…	*Grow*
100	Add regeneration layer (Aw, Pb and Bw)
…	*Grow*
110	Add regeneration layer (Sw and Pj)
…	*Grow*

The first event is the stand establishment. The stand establishment is done at year 10. The establishment event is designed to occur ten years following germination. It was done this way because stands are established (regenerated) with breast height age greater than zero. So the trembling aspen component that is being 'established' at year ten is four years old at breast height; and ten years old in total. A second event is used to bring in white spruce trees that are intended to contribute to the main canopy by the first stage harvest. These stand conditions are grown for 30 years, at which time a 'regen' event is used to emulate understory establishment (planted or natural). This understory establishment is done at year 50 in the projection.

Following a further 60 years of growth, we arrive at the preharvest treatment conditions that existed in the treatment areas. 'Thin' events, intended to simulate the treatment activities, are then conducted within MGM. Removal rates were selected to emulate densities found in post harvest conditions. Different removal rules were used to emulate theoretical expectations of treatment outcomes.

Ten and twenty years following thinning, regeneration layers are added to occupy the excess growing space. Densities for this cohort are based on generic two-stage tending and harvesting treatment averages. Following the addition of the second cohort the stand is grown in MGM for an additional 100 years. The results of this simulation provide a basis of evaluation of different intensities of treatments and based on the models that are used in MGM it will provide some insight into the optimum timing of the treatment stages. The full crop plan for this simulation is included in the Appendix VI (MGM Crop Plans).

4.4.2 Simulation Results

The conifer and deciduous density plotted over time is shown in Figure 4-5. The density changes with the various regeneration and thinning events as they are modeled along the projection timeline. This projection was designed to emulate the true two-stage tending and harvesting treatment both before treatment and five years post treatment, the two periods for which we have some record. At year 160 in the projection, which corresponds to the 70 years following treatment in the earlier projections, the densities do not closely reflect the densities predicted when empirical treatment data is projected. Seventy years following first harvest MGM has projected a conifer density of 481 stems per hectare and a deciduous density of 2,358 stems per hectare. The conifer density is larger than those projected with empirical treatment data (Table 4-1). The deciduous density is close to those projected with empirical treatment data (Table 4-2).

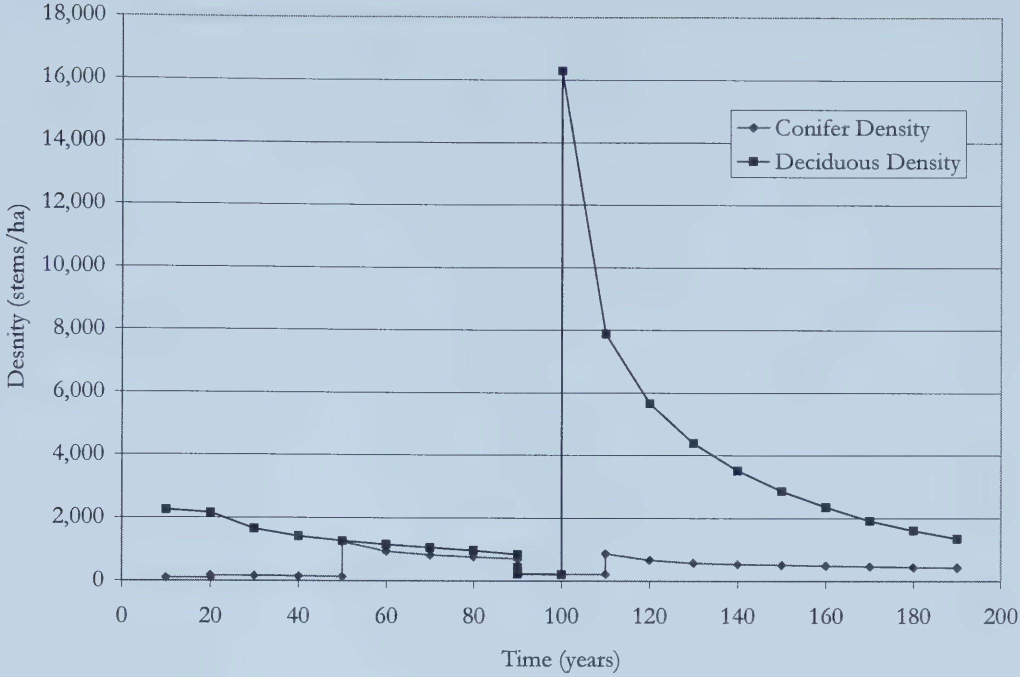

Figure 4-5: Treatment mean conifer and deciduous density simulation projection

Figure 4-6 shows yields that are predicted over the two-stage tending and harvesting simulation. At year 90, where the first stage harvest is performed a total volume of 230m³/ha of deciduous and 32m³/ha of conifer is captured. The projection continues and we can see that the volumes for deciduous and conifer, respectively, at year 160 (70 years following first stage harvest) are 265m³/ha and 123m³/ha. Year 160 represents the peak for deciduous volume.

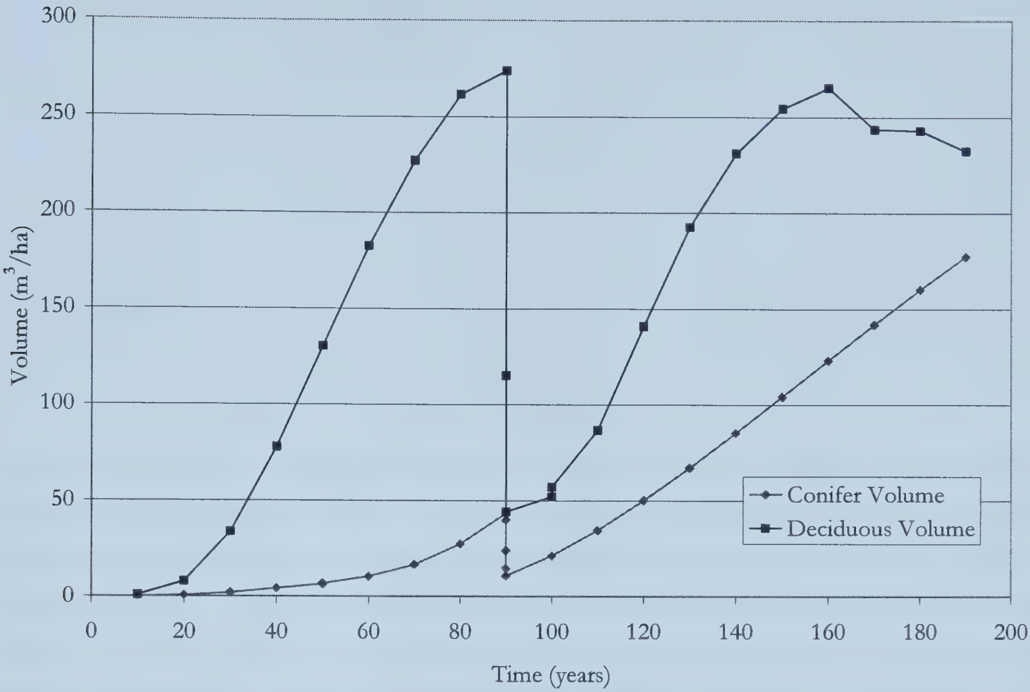

Figure 4-6: Treatment mean conifer and deciduous volume simulation projection

4.5 Discussion

The two-stage tending and harvesting system is a silviculture treatment consisting of stand manipulation in the way of tree removal. Thus, it is a treatment that removes trees from the stand that are merchantable, while creating more available growing space and resources so that residual trees experience reduced competition and elevated growth. The idea is to get those trees from the site which are merchantable now, let those that are not merchantable mature, and recruit a new cohort of fast establishing and growing deciduous trees along with them for harvest in the future (Brace and Bella 1988).

MGM has the capability to simulate and project such treatment conditions. MGM's height and diameter increment functions adjust the growth of a tree as the conditions in the stand are altered. Height increment, being a function of competitive position, will increase as the competition is reduced in the stand. The diameter increment function is based on competitive position and a spacing factor, and thus, will increase as the competition is reduced and/or as the spacing factor is increased. As the treatment is carried out in the MGM environment, residual trees will have greater height and diameter increments and thus faster growth rates than they once had in pre-treatment conditions.

One detail of treatment response that MGM does not model is lag time to response. Often following a thinning or exposure to additional resources, there is a lag time associated with response, due to various stresses and the inability of an individual tree to utilize the additional resources without first morphologically changing to accommodate them (Urban et al. 1994, Klinka et al. 1992). An event indicator variable could be included in the growth and mortality functions in MGM. This indicator variable could act as a flag for stands in the first few years following a thin event. This variable could adjust the level of growth and mortality in the short term following the event. This may be one way to model a lag time in response. The fact that MGM does not consider this lag time is likely not a problem as the projections that MGM is used for in this study are longer term (70 years), and thus should have very little impact on the resulting stand characteristics.

Another primary concern is how MGM treats the probability of survival following treatment. In treatments such as this, where the dominant trees in the stand are removed, the residual trees can often undergo considerable stress. Any change in microclimate, of a tree, can result in a stress for that tree (Greene et al. 1999). Wind and sun stress being the two primary stresses on such a tree (Hale and Orcutt 1987, Mathews 1989). This is expected to result in an increased mortality rate; thus, a decreased probability of survival. The mortality function in MGM is driven by a number of variables, all which would change with the treatment activity. However, the existing model will not capture the actual stress of the change. Thus, for the treatment simulation it is necessary to implement an additional reduction as a thinning event to account for the loss expected with initial mortality.

In the author's opinion the primary factor that will determine the success or failure of this type of treatment is not a result of the elevated growth rates that occur following treatment, but rather is a direct function of how well the treatment was operationally executed and how great the initial mortality rate is. In the treatments studied here, a high within treatment variation was observed. This variation is thought to be a result of two things; natural random stand conditions and operator error. If sites were selected for their uniformity in the understory and operators were sufficiently trained in the harvesting sequence it is expected that this variation would be reduced and the respective treatments could better be evaluated. The 'Mod Shelter', '50m Strip' and '100m Strip' treatments all have projections that are not significantly different than one another. Maybe what requires additional work is an operational reduction of the within treatment variation.

The initial mortality would be a function of local environmental conditions in the years following the treatment (i.e. amount of rain, severity of wind storm events, drought conditions, etc.). If extreme conditions are present before the trees become more wind firm a higher mortality event may occur. This makes the level of this initial mortality event difficult to predict. However, when variations on a treatment are conducted in a localized area, under similar environmental conditions, as is observed with

this study, a comparison between the treatments is of use; this does not allow us to make any solid conclusions outside of the environmental conditions that occurred following the execution of these treatments.

In the empirical treatment projections, by 70 years following treatment both deciduous densities and conifer densities approach a reasonable level relative to the extreme recruitment densities measured following treatment. Deciduous densities level a little for each treatment as the densities fall below 10,000 stems per hectare. This increased probability of survival is directly related to the threshold density of 10,000 stems per hectare for the juvenile trees. This is the models way of dealing with extreme recruitment densities, which are common when vigorous natural deciduous regeneration is being considered. In juvenile stand conditions with high densities, the density of the stand is likely the most important factor in the model to make good assumptions about probability of survival, rather than growth rates. There is little empirical data in this density of stand, likewise empirical data is lacking in very low-density stands. This introduces a potential weakness when MGM projects stands with these densities.

The total volume for deciduous and conifer, as derived by MGM over the projection, provides us with estimates of what volume could be expected for the second-stage harvest given the empirical starting conditions. The 'Uncut Control' depicts a smooth conifer and deciduous volume projection as the mature stand ages. The conifer volume in the projections for the 'Mod Shelter', '50m Strip' and '100m Strip' treatments reach a peak at 45 years following treatment. This appears to be due to the stand basal area per hectare limit being reached, at around 55 m^2/ha for mixed stands. This modeled limit appears to favour the deciduous trees in the stand and, as a result, is killing off the larger white spruce trees in the stand; thus, the resulting drop in conifer volume after 45 years following treatment. This relationship does not seem to be intuitive, as it would be expected that the well-established white spruce, with an age of approximately 105 years, would not fall out of the stand. This basal area limit is one area in MGM, which may require some additional work to better represent the stand conditions that these treatments produce.

Within the full simulation at 70 years following the first harvest treatment the conifer volume does not closely reflect the empirically based projections. The conifer volume in the full simulation at 70 years following treatment is higher by about 130 m^3/ha than the other empirically based projections. The conifer volume is also observed to continue increasing throughout the entire projection. This is in contrast to the empirical based treatment projections, which show a peak conifer volume at 45 years following treatment. The full simulation differs from the empirical based treatment projections, as the stand basal area limit is not reached in the simulation. In the full simulation the stand basal area peaks

at 70 years following first stage harvest, at just over 49 m^2/ha. This corresponds with the peak in deciduous volume in this projection.

The full simulation provides an overall look at the scenario. Volume captured in the first harvest is illustrated here and indicates what volume would be captured during the second harvest depending on when the second harvest is conducted. According to the empirical based projections it appears that it would be of benefit to conduct the second harvest earlier than Brace and Bella (1988) indicate. It appears that conifer volume could be maximized at around 45 years following treatment, even while deciduous volume continues to increase beyond this point. The full simulation contradicts this finding, while depicting a conifer volume that continues to increase through out the projection and a deciduous volume, which reaches a peak at 70 years following overstory harvest. Based on the entirely theoretical simulation, Brace and Bella (1988) had the right idea with an anticipated second-stage harvest at 60 to 70 years following the first-stage harvest.

The deciduous/conifer volume results from both the empirical projections and the full simulation are contrary to those as described by Brace and Bella (1988). Brace and Bella (1988), based on various assumptions regarding residual densities and characteristics estimated that the conifer component of the stand would become the dominant component of the stand in the second stage of the treatment, with expected conifer volumes far exceeding deciduous volumes in the second stage. In this study's projection the reverse was found with deciduous volumes far exceeding conifer volumes in the second stage of treatment. This is due to Brace and Bella's (1988) modeling assumptions not being met. Brace and Bella (1988) assumed higher viable residual white spruce densities than were reached with these treatments. More work is required to evaluate if higher viable residual white spruce densities are even possible.

Although it is early in the project it is still desirable to make some initial projections. As the length of projection increases the variation and potential deviation from actual conditions will increase. Thus as more data becomes available (i.e. data from 20 years after treatment) similar projections could be conducted and results reassessed.

4.6 Conclusion

MGM provides a reasonable projection of stand conditions following the first-stage of a two-stage tending and harvesting treatment. The following was found when 70 year stand projections were compared between the 'Uncut Control' area and the 'Mod Shelter', '50m Strip', '100m Strip' and 'Clearcut' treatments:

- With a 70-year projection from treatment conifer densities were not different between treatments.

- The 'Uncut Control' was found to have a smaller projected deciduous density than all of the four treatments. There also appeared to be large differences in the projected deciduous densities between the treatments, with the 'Mod Shelter' treatment having the lowest deciduous density (2,074 stems/ha) in the range of 400 stems per hectare less then the other treatment.

- The 'Uncut Control' has higher projected conifer volume (190 m^3/ha) and the 'Clearcut' treatment has smaller projected conifer volume (2 m^3/ha) than the other 3 treatments (~75 m^3/ha).

- The 'Uncut Control' projected deciduous volume (381 m^3/ha) and the 'Clearcut' treatment projected deciduous volume (358 m^3/ha) are larger than the '50m Strip' and '100m Strip' mean projected deciduous volumes (~300 m^3/ha).

MGM also provided a valid full treatment projection. Lending to the estimates of yield acquired or lost during the various stages of the treatment. The results from both the empirical projections and the full simulation produced results contrary to those as described by Brace and Bella (1988), as deciduous volumes remained the dominant component of the stand following first stage harvest. This is likely due to Brace and Bella's (1988) assumed residual densities not being achieved, and therefore not a fault of MGM. The author feels that MGM can provide the bases for evaluating existing stands for this type of treatment. The operational application is apparent.

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Chapter 5

CONCLUSION

The two-stage tending and harvesting treatment appears to work well in consort with the common mixedwood stand type of trembling aspen (*Populus tremuloides*) over white spruce (*Picea glauca*). With early monitoring of the growth and yield characteristics of a variety of two-stage tending and harvesting treatments some differences can be detected. This thesis compared and contrasted the various two-stage tending treatments in three ways. First, the residual white spruce cohort was compared between treatments. For this cohort individual tree characteristics such as height and diameter were compared, as well as stand level characteristics such as density and volume per hectare. Secondly, the regeneration cohort was compared between treatments. Mean heights and densities for conifer and deciduous were compared between treatments respectively. Finally, projections, made with the existing post treatment data, are compared. Projected deciduous and conifer, volumes and densities are investigated.

Residual White Spruce Cohort

Following the first-stage harvest of the two-stage tending and harvesting treatments, a number of conclusions can be made regarding the residual white spruce cohort. The residual white spruce cohort did not differ in their height yield and increment. This, in part, may be due to the large within treatment variation that was observed for the height measurements. A longer period between measurements would be of use for further evaluation of height increment.

The diameter response, as evaluated with a diameter increment five years post treatment over a diameter increment five years pre-treatment, depicted that individual white spruce trees experienced high levels of release. The potential for increased diameter growth appeared to directly relate to the level of release of individual trees. Thus, with the greatest change in the competitive status of an individual tree the greatest potential for change was observed in diameter increment ratio. With this finding we see that individual white spruce trees in the '50m Strip' and '100m Strip' treatments, the treatments that were released the most, have the greatest increase in diameter increment.

In the early stages following treatment, with the exception of the 'Clearcut', which had a residual white spruce density of zero, all of the treatments had insignificant differences in their white spruce residual densities. A high variation in this characteristic may have contributed to this finding. The densities are mechanically altered by way of the harvesting treatment activities. If stand conditions are relatively uniform, it is expected that the residual density can be relatively well controlled within the treatment activities.

Regeneration Cohort

The regeneration cohort can establish vigorously, with high densities of deciduous trees competing to get established in the excess growing space. The density of deciduous regeneration appears to be inversely related to the amount of residual tree retention, with the 'Clearcut' showing a significantly larger deciduous regeneration density. Conifer regeneration densities showed an insignificant difference between treatments and thus, the specific treatment activate had no measurable effect on the density of conifer regeneration.

The mean height and the mean height increment appear to be inversely related to residual tree retention, with the 'Clearcut' treatment as an exception. As less competition is present in the way of residual trees the regeneration appears to be growing with increased vigour. The '50m Strip and '100m Strip' treatments produce a growing environment for the regeneration cohort which saw a significantly greater height increment than the 'Mod Shelter' treatment.

Stand Treatment Projections

MGM provides a reasonable projection of stand conditions following the first stage of two-stage tending and harvesting treatments. The 'Clearcut' was observed to have smaller projected conifer volumes and greater projected deciduous volumes than the 'Mod Shelter', '50m Strip' and '100m Strip' treatments. This corresponds to the lack of residual white spruce retention in the 'Clearcut' treatment and the resulting high density of trembling aspen and balsam poplar recruitment. Very little can be said based on the projection of the three different patterns of two-stage tending and harvesting treatments, as there was little variation in mean volume and density characteristics between them. At the early stage following treatment they are reasonably similar to one another and have a relatively high within treatment variation thus making the projection of these conditions difficult to differentiate.

MGM also provided a valid full treatment projection, which provides estimates of yield utilized or lost during the various stages of the two-stage tending and harvesting treatment. MGM can provide the bases for evaluating existing stands for this type of treatment. The operational utility of this type of modeling is apparent. Both the full simulation and the empirical treatment projection provided results contrary to previously published results (Brace and Bella 1988). Brace and Bella (1988) predicted conifer to be the dominant stand component in the second-stage of the treatment. However, this was not the finding in this study due to assumptions about residual densities not being met. It is yet to be determined if the previously published post treatment stand characteristics are even operationally attainable. More work will be required here.

This seems to be a viable harvesting option when conducted correctly. Care must be taken during harvest operations and site characteristics should be carefully considered. This scenario may be most

appropriate in sensitive areas where stand structure retention is an important factor. The additional costs associated with carrying out this type of treatment may make this an unfeasible harvesting option when strictly considering timber values in relation to harvesting expenses.

It is important that consideration be given to the site of harvest. First, the existing stand must meet the species composition needs for this harvest to even be considered. Second, one should consider typical wind conditions in a given area. If strong gusting wind is a common occurrence in an area it should not be considered for this treatment. Finally, the typical site moisture should be considered. Wetter sites are more prone to wind throw then drier sites.

The findings from this study are from a localized experiment conducted in Northern Alberta lower foothills natural subregion. The use of these results in other areas should only be used as a general guide of concepts and factors to consider in areas in which a two-stage tending and harvesting scenario may be of interest.

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Brace, L.G. and I.E. Bella, (1988). Understanding the understory: dilemma and opportunity. Pages 69-86 in J.K. Samoil, ed. Management and utilization of northern mixedwoods. Proc. Symp., April 11-14, 1998, Edmonton, Alberta. Can. For. Serv., North. For. Cent., Edmonton Alberta. Inf. Rep. NOR-X-296.

Appendices

A.1 Appendix I (Treatment Summary)

The following includes excerpts from an information report published by the Canadian Forest Service (Navratil et al. 1994). This section describes the five treatment areas that were sampled: 'Uncut Control', 'Clearcut', 'Mod Shelter', '50m Strip' and '100m Strip' treatments.

A.1.1 'Uncut Control' Block: Uncut mature aspen over immature spruce

The control block is an area that was left uncut. This stand is just west of the 'Mod Shelter' treatment.

A.1.2 Block 'Clearcut' Treatment: One-Pass Control Harvest

Harvest took place in late fall 1993; operational "avoidance" was considered for immature spruce while removing merchantable deciduous overstory stems in one pass. "This provided minimal wind protection for immature spruce only in the narrow band adjacent to the west (windward) edge of the block" (Navratil et al. 1994).

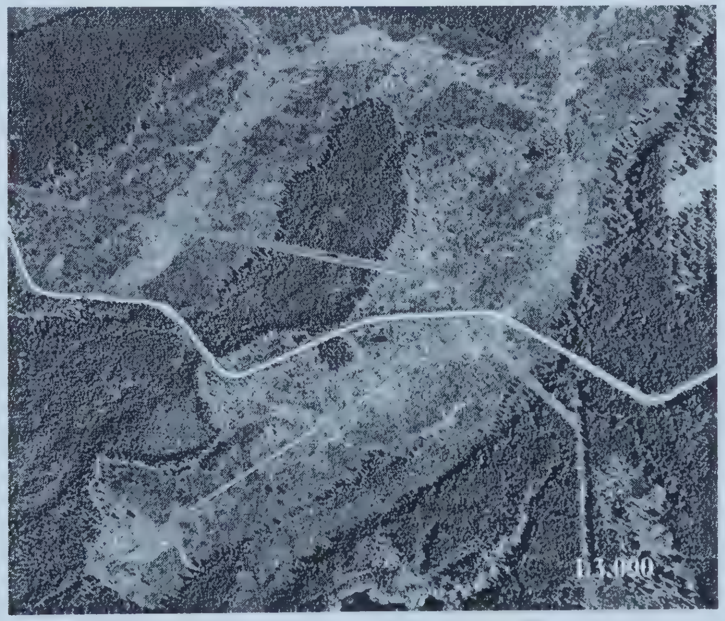

Figure A-1: Aerial Photograph of the 'Clearcut' Treatment (courtesy CFS)

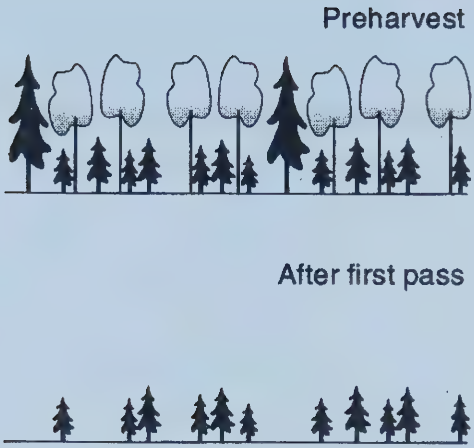

Figure A-2: Diagram of the 'Clearcut' Treatment (Navratil et al. 1994)

Figure A-2 depicts the planned 'Clearcut' treatment. Following the harvest very few residual white spruce trees were observed. Thus, the treatment appeared to be more of a clearcut than the figure would indicate.

A.1.3 Block 'Mod Shelter' Treatment: One-Pass Modified Uniform Shelterwood

Harvest was carried out during late winter 1994. In an effort to not unnecessarily forego deciduous volume in the way of protective buffers, this block also contains an area of One-Pass Control Harvest. The control harvest was used in areas where spruce stocking was low to moderate. However, the long-term growth and yield project was only interested in the One-Pass Modified Uniform Shelterwood area.

"In areas where immature spruce stocking was moderate-to-high, machine corridors were established at 25 m intervals perpendicular to the prevailing wind. All accessible deciduous volume was removed in one pass, leaving a 5 m uncut strip midway between corridors. Machine corridors, roads, and landings should result in removal of about 40% of the forest cover from the block. About 15% of the merchantable deciduous will be sacrificed in the 5 m buffer strips. This should provide repetitive windbreak effects and result in a medium-to-possibly high level of wind protection for immature spruce" (Navratil et al. 1994).

Figure A-3: Aerial Photograph of the 'Mod Shelter' Treatment (courtesy CFS)

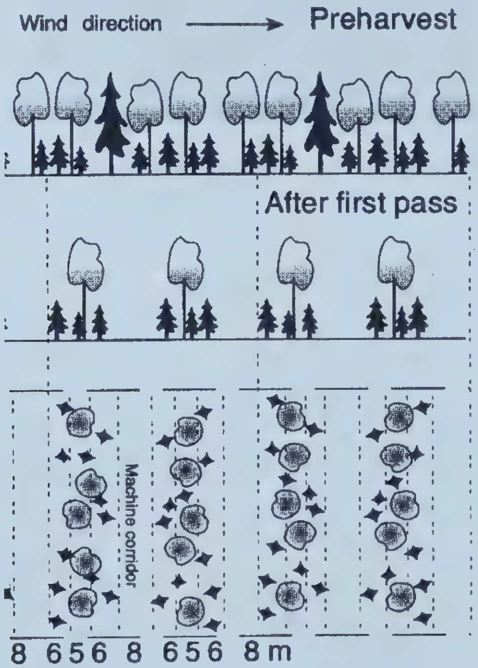

Figure A-4: Diagram of the 'Mod Shelter' Treatment (Navratil et al. 1994)

A.1.4 Block '50m Strip' Treatment: Two-Pass 50m Alternate Strip

First-pass harvest took place in early fall 1993; using a two-pass system that includes six segments (A, B, C, D, E and F) each with two strips. All merchantable deciduous volume in strip 1 was harvested in

1993 and all merchantable deciduous volume in strip 2 was harvested in 1998. All strips are 50 m wide. Machine corridors were placed 20m apart and ran perpendicular to the wind, as did the strips. Thus, each strip contained two machine corridors and three residual areas. These five years between passes should provide some time for residual spruce to become more wind firm resulting in a medium level of wind protection. After the second pass, the level of protection will be low to very low because of the large open area, which is 300 m wide (Navratil et al. 1994).

Figure A-5: Aerial Photograph of the north component of the '50m Strip' Treatment (courtesy CFS)

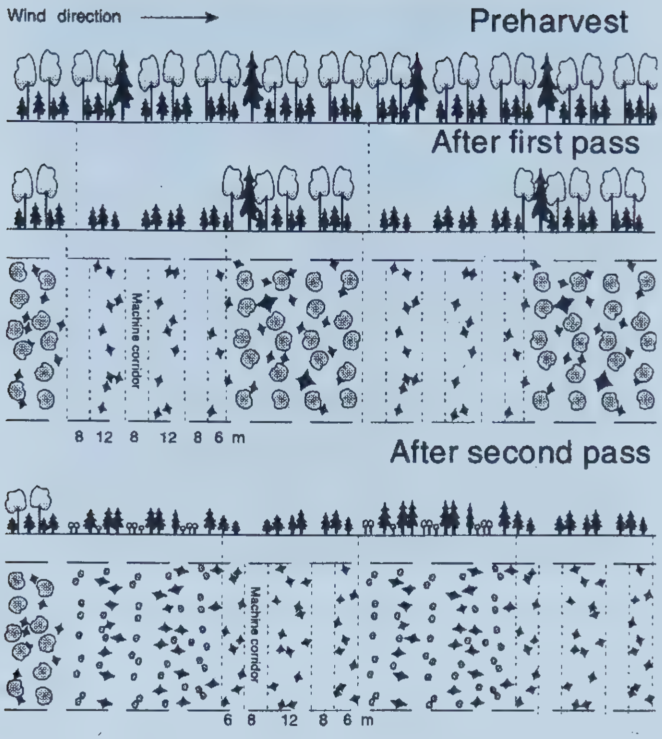

Figure A-6: Diagram of the '50m Strip' Treatment (Navratil et al. 1994)

A.1.5 Block '100m Strip' Treatment: Two-Pass 100m Alternate Strip

First-pass harvest was carried out in winter 1994, using a two-pass strip system that includes four segments (A, B, C and D) each with two strips. All merchantable deciduous volume in strip 1 was harvested in 1994 and all merchantable deciduous volume in strip 2 was harvested in 1998. All strips are 100 m wide and oriented perpendicular to prevailing winds. A low to medium level of wind protection for immature spruce is expected from the wide strips in the years between the first and the second pass. After the second pass the level of protection will be very low, especially in second-pass strips, because the large open area of 800 m in the direction of prevailing winds (Navratil et al. 1994).

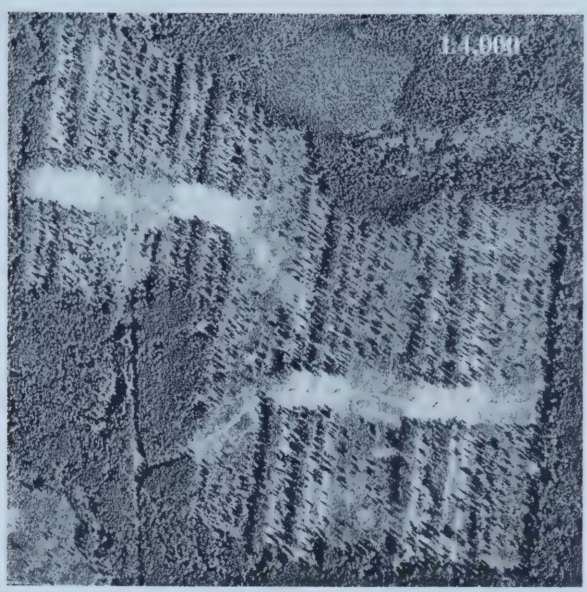

Figure A-7: Aerial Photograph of the '100m Strip' Treatment (courtesy CFS)

A.1.6 Literature Cited

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A.2 Appendix II (Sampling and Measurement)

A.2.1 Original Timeline

The timeline of planned first stage harvest operations and tree measurements are outlined in Table A-1.

The second pass harvest is only applicable for those treatments, which are two pass treatments.

Table A-1: Timeline of Harvest Operations and Measurements

Year	Harvest Operations	Measurement
1993	1st pass harvest	CFS transect established
1994		
1995		
1996		
1997		
1998	2nd pass harvest	G&Y PSPs established & measured
1999		G&Y PSPs measured
2000		

A.2.2 Sampling Strategy

Throughout the four selected treatments ('Mod Shelter', '50m Strip', '100m Strip', and 'Clearcut') and the 'Uncut Control' area, 58 PSPs, in total containing 116 sub-plots, were established in the summer season of 1998. For the 'Clearcut' treatment eight 20 by 30 metre (0.06ha) PSPs were randomly established throughout the treatment area. Two 20 by 30 metre (0.06ha) PSPs were randomly established in the 'Uncut Control' area located west of the 'Mod Shelter'. The remaining treatments had four 'blocks' selected from them for sampling. The 'blocks' were equivalent to the first pass strips. In each of these selected blocks four 10 by 60 metre (0.06ha) PSPs were established. Two of these PSPs are aspen regeneration plots randomly established along machine trails. The other two are residual spruce plots randomly established in-between the machine trails where understory spruce trees were protected during harvest. Each PSP has two 2 by 2 metre subplots located in opposing corners of the plot (Northwest & Southeast). The layout of the machine corridor PSPs and the residual PSPs and their respective subplots are depicted in Figure A-8. Note that the figure is not to scale.

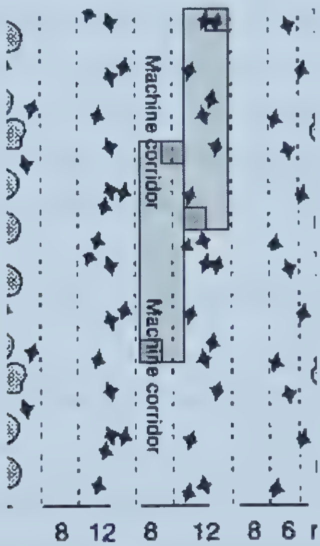

Figure A-8: Diagram of Plot Layout

Plot Size & Shape

When considering the sampling of environmental data the square shape of the PSP is important as it significantly reduces the 'edge effect'. The term 'edge effect' when talking about sampling typically refers to the problem with bias that can arise when sampling as areas near the edge of the forest have a smaller probability of being sampled. This can be a problem because in a random sample all areas should have an equal chance of being sampled. Here, 'edge effect' refers to the concept of area of

influence. Each tree is considered to have some area of influence that is some function of its relative height.

In growth and yield modeling one is interested in accounting for an individual's growth based on information of those competing trees in the circle of influence. Thus we also want to sample the trees around the subject tree. Typically, PSPs are not set up for one tree but more commonly are simply a preset size and dimension.

Historically, treatments are best represented by PSPs that are 20 by 20 metres (0.04ha). This area provides the greatest marginal return. A PSP must be representative of the treatment so locating these plots is partially subjective. In this project both 20 by 30 metre (0.06ha) and 10 by 60 metre (0.06ha) plot dimensions were used. In the control areas where treatment did not restrict the dimensions of the PSP 20 by 30 metre plots were used. However, in the treatment areas plots were needed that fit in the treatment along areas where residual spruce trees were protected (residual strips) and along areas where residual spruce trees were not protected (machine corridors); thus, 10mx60m plots were needed. These plots were oriented parallel to the treatment allowing any given plot to represent solely one treatment, one block and either a residual protected area a machine corridor. This design allows us to compare the different growth, regeneration, mortality, species and size factors for treatment and strip dependence. If one of these factors is found to be significantly different among treatments or strips than it can be considered treatment or strip dependent respectively.

Plot Selection

'Mod Shelter', '50m Strip', & '100m Strip': Each plot is 60 metres long by 10 metres wide and was randomly selected within the treatment in the machine corridor or residual strip. In the 'Clercut' treatment and the 'Uncut Control' each plot is 20 metres by 30 meters. Locations for these plots were random throughout the respective areas.

Each plot is marked with a 6 foot orange plastic rod in the main corners. Pigtail markers tied with orange ribbon further delineate the subplots. A metal tag was placed in the inside corner of each subplot (i.e., on the inside pigtail).

A.2.3 Measurements

A detailed outline of the procedures of data gathering was used in the summer of 1998. Data on the vegetation was also collected in the summer of 1998. Vegetation data included tree species, total tree height, height increment, dbh, root collar diameter, crown diameter, crown ratio, age, status of the tree, and information on grasses and shrubs. The vegetation data collected in the summer of 1998 was collected again from existing PSPs in the summer of 1999. If there were more than 500 trees in a single plot, that plot was halved. Trees over 1.3 metres were measured in the half (randomly chosen). All

mature trees were measured in the entire plot. This only occurred in the '50m Strip' and '100m Strip' treatments. A subjective call of what constituted a "mature tree" was made in the field; typically this corresponded with trees that have a dbh greater than 9 centimetres.

Treatment Numbering

A number, from the treatment maps, corresponds to each treatment as follows: F12 – 'Clearcut', F62 – '100m Strip', F61 – '50m Strip', F11 – 'Mod Shelter', and Control 2 – 'Uncut Control'.

Block

The block designation comes from the treatment maps. A number was simply added to the existing block letter to give, for example, A1 and A2. In all cases, 1 refers to the regenerated areas and 2 refer to the residual stand areas. There was no block distinction on the maps but one was arbitrarily created in the field for the sake of consistency across the treatments.

Plot #

Self-explanatory. Each block has two plots with the exception of the control, which has only 1 plot per block.

Subplot

The subplot designation is a simple two-letter designation indication either the South-West (SW) or the North-East (NE) subplot. Subplots are always located in these two corners of the main plot.

Tree #

Trees within each subplot and main plot were numbered beginning with 1 and worked through the plot consecutively.

Species

The following codes were used for species: **Aw** - trembling aspen (*Populus tremuloides*); **Pb** - balsam poplar (*Populus balsamifera*); **Bw** – paper birch (*Betula papyrifera*); **Sw** - white spruce (*Picea glauca*); **Pj** - jack pine (*Pinus banksiana*)

Root Collar Diameter (RCD)

Root Collar Diameter was recorded for trees in subplots only. A calliper was used to read diameter to the nearest millimetre, though the values were recorded as decimal centimetres. In general, RCD was taken at the top of the organic horizon. Where a pronounced swelling at the base of the bole exists, it is generally avoided, with RCD taken at the nearest point above it. Judgement is required in special circumstances such as stump sprouts.

Diameter at Breast Height (DBH)

On saplings, a calliper was used; a diameter tape was used on the mature trees. In either case, values were read to the millimetre. For smaller trees, it was necessary to take dbh on the new growing shoot. dbh was always taken at a live shoot if possible, unless only the dead top existed at 1.3 metres height.

Height to Crown Base (HCB)

In general, it is the height from ground level to the lowest live foliage. Judgement is again needed in circumstances such as in aspen where branches may attach to the stem at a significantly lower height than the actual leaves begin. Where possible, we measured to the lowest live leaves/needles as opposed to the base of the live branch. For smaller trees, this measurement was taken directly with a tape measure and read to the nearest centimetre. For larger trees, where a clinometer was being used to determine total height, a clinometer was used regardless of whether the base of the crown was at a measurable height or not.

Height

This is the total height as measured from the ground level (as with HCB) to the top of the tree. The top is not defined as branch only, but also leaves. In the case of a dead top, then, the top of the dead branch is read for height. For stump sprouts, the stump was included as part of the height. As with HBC, for smaller trees, this measurement was taken directly with a tape measure and read to the nearest centimetre. For larger trees, a clinometer was used. Height is generally recorded as the <u>vertical</u> distance from ground level to the top of the tree.

Height Increment

This value was recorded for trees in subplots only. It was often difficult to determine the increment for aspen, which was infected with Shepherd's Crook. In general, measurements included the crook as part of last year's growth. Where this crook was broken off, a best estimate was required. The leader length was taken with a tape measure and recorded to the nearest centimetre. The margin of error was deemed to large if estimates were made for increment on mature trees, which happened to fall in the subplots, as a clinometer would have to be used.

Damage Codes

A maximum of three damage codes were recorded for each tree, regardless of species. A list of damage codes was provided, in order of priority.

Crown Diameter

This measurement was recorded at North-South and East-West bearings which generally coinciding with the orientation of the plot boundaries. The values were recorded to the nearest centimetre.

Age

Age was recorded for all qualified conifer species found in the main plot (i.e., those greater than or equal to 1.3 metres in height). For some trees, it was possible, and more prudent, to read the age directly from the tree by counting branch whorls, as opposed to coring. For larger trees, an increment corer was used.

Shrubs/forbs/grasses

All plants within the subplots that could be identified were listed, in no particular order. A count was done for each species except those that a reliable estimate could not be obtained. An estimate of percent cover was also taken.

A.2.4 Shortcomings in Design

There were a number of shortcomings identified in the sampling design. PSPs were intended to sample two areas within a treatment, the machine corridors and the residual strips. Both of these areas are strip areas as represented by an 8-metre machine corridor and a 12-17 metre residual strip depending on the treatment. Plots with a dimension of 10m by 60m were used to sample these two areas. Thus, the dimension of the plot exceeded the width of the machine corridor strips. The plots sampled to represent the machine corridor area cannot be said to exclusively represent this area as some of the plot will likely fall in the residual strip area. In order to rectify this shortcoming it will be desirable to stem map the trees with each plot so that the true boundaries of the machine corridors and the residual strips can be identified. Additionally, stem mapping will allow partitioning the plot shorter segments (e.g. 10x10 or 10x20 m) so that the influence of nearby trees could provide better indications of competition.

A second shortcoming of the sampling design was the location of the subplots. The subplots were located in the SW and NE corner of each PSP. Thus, they were always on the edge of machine corridors and residual strips often with subplots side by side in an adjacent set of plots, one representing the machine corridors and one representing the residual strips. This effectively minimized the variation among subplots located in the machine corridors versus those in the residual strips. Upon remeasurement one may one to consider relocating these plots to the centre of the PSP or randomly locate them within the PSP so that both the centre and the edge of the strips can be effectively represented.

A third shortcoming is the fact that some of the PSP upon establishment and first measurement had to be halved in size for measurement due to the extremely high density of trees in the plot. This had to be done in order to complete plot measurement on budget. The densities in plots that were halved are expected to be much lower upon remeasurement and thus, the expectation is that the trees throughout

the full plot will be tagged (if not already tagged) and measured. There should be no instances of half plots upon next remeasurement.

The final shortcoming of the PSP establishment and measurement is the timing of the first measurement. The PSP were established and first measured five years following the first-stage harvest. This makes it imposable to make conclusions about what was happening to the stand in the first five years following harvest. It would have been ideal if PSPs were established either pre-treatment or immediately post-treatment so the early stand dynamics could have been captured. While there is nothing that can be done to change this shortcoming for this study, it is worth noticing so that similar mistakes are not made on future projects.

A.2.5 Recommendations for Further Plot Measurements

In the year 2003 it will be 10 years since first-stage harvest. This would be a good time for PSP remeasurement. The following is a point form list of remeasurement recommendations:

- Conduct a full remeasurement of all existing plots in 2003. Repeat all of the same measurements as conducted at time of establishment. (i.e. height, dbh, height to live crown, condition, etc.). Tag and measure ingrowth trees. This includes a full measurement of subplots as well as main plots.
- Tag and measure the trees taller than 1.3 metres in the full PSP (.06ha) in the machine corridors. Previously only subplots were measured in these plots.
- In cases where PSPs were halved during establishment, due to excessive densities, both halves should be measured if density has dropped to an acceptable level. Trees in the previously unmeasured half will need to be tagged and identified for separation in the analysis.
- Consider stem mapping the trees in the main PSPs. This would allow for a true separation the machine corridors from the residual strips and to allow for subdivision of the PSPs as required.
- In addition to the remeasurement of existing subplots. Consider establishing new subplots randomly throughout each PSP. This would provide a more fair representation of the differences between the machine corridors and the residual strips.

Following the next measurement successive measurements might be considered at an interval of five or ten years in order to capture the variation in the treatment dynamics over time. Note also that there are other similar harvesting treatments being carried out throughout Alberta. Sharing of results and findings from this study and looking at results and findings from other studies will contribute to the overall knowledgebase for this topic.

A.3 Appendix III (Sw Height/DBH Model)

To calculate tree volumes both dbhs and heights are required. As not all heights were measured for all of the trees it is important to understand the relationship between height and dbh. This relationship specific to each treatment area will allow us to estimate heights of trees were only dbh was recorded.

A common equation used to express the relationship between diameter and height is the Chapman-Richards equation (Equation A-1). This equation is appropriate for modeling white spruce in Alberta (Huang et al., 1992). So a Chapman-Richards equation was used here to fit the relationship between height and dbh.

Equation A-1 $$Ht(cm) = 130 + b(1 - EXP(-c \times DBH))^a$$

In order to satisfy the assumption of equal error variance a weighting factor had to be included in the analysis. The weighting factor used is outlined in Equation A-2.

Equation A-2 $$\omega_i = 1 / DBH^2$$

This weighting factor was determined by visual assessment of the studentized residual plot output provided by SAS®. Huang et al. (1999) used a similar weighting factor for the development of height-diameter models for Alberta ecoregions.

Model coefficients were generated by fitting the data to a Chapman-Richards equation. The data provided for relatively strong fits, as expected, based on a typically strong relationship between height and diameter. These strong fits are depicted with the large adjusted R-square values found in Table A-2.

Table A-2: Coefficients and model characteristics for height-dbh equations

Treatment	A	B	C	N	Adjusted R^2	MSE
'Uncut Control'	1.512037	22.3539	0.080223	77	0.9529	0.0235
'Mod Shelter'	1.447529	28.1226	0.051454	273	0.9609	0.0156
'50m Strip'	1.585736	23.25887	0.072997	150	0.96	0.021
'100m Strip'	1.383449	29.21071	0.044625	117	0.9537	0.0189

These height-dbh relationships are used on a treatment specific basis to estimate the unmeasured heights of residual white spruce trees. With heights and dbhs for all white spruce trees, volume can be calculated by way of Alberta local volume functions (Huang, 1994).

Literature Cited

Huang, S., D. Price and S.J. Titus, 1999. Development of ecoregion- based height-diameter models for white spruce in boreal forests. Forest Ecology and Management. 129 (2000) 125-141.

Huang, S., S.J. Titus, and D.W. Wiens. 1992. Comparision of nonlinear height-diameter functions for major Alberta tree species. Canadian Journal of Forest Research. 22: 1297-1304.

Huang, S. 1994. Ecologically-based individual tree volume estimation for major Alberta tree species. Alberta Environmental Protection, Land and Forest Services, Forest Management Division.

A.4 Appendix IV (Field Location)

Directions to Treatment Areas

- Head North out of Manning on highway 35 for about 24km
- Turn left on to Chinchaga Forestry Road
- Go for 34km on this road
- Turn left at Sign ("South Hotchkiss Compressor Station 9km")
- Go 3.5km and come to a bridge
- 1.5km from bridge on left side find F6-1 B and C
- Another .5km on left side find F6-1 E and F
- Turn right to get to clear-cut at sign (Hotchkiss River Timber Demonstration) 2km to clearcut
- Just up road from clear-cut turn off is the Road Juncture
- Turn left at road juncture to get to the 'Uncut Control', 'Mod Shelter', and '100m Strip'
- All road Markers for control and 'Mod Shelter' are measured from the road juncture
- It should be about 1km to the mine site where the POC1 is for '100m Shelter'

A.5 Appendix V (Sample SAS® Code)

A.5.1 Simple ANOVA

The following is SAS® code for a simple analysis of variance. In this excerpt of code we are testing to see if there is any significant difference in the mean diameter increment between treatments.

```
PROC GLM data=d_inc;
  CLASSES trt;
  MODEL dbh_inc=trt/ss3;
  MEANS trt/TUKEY lines; /*tukey test*/
  LSMEANS trt/pdiff; /*least squares means*/
RUN;
```

A.5.2 ANCOVA

The following SAS® code is for an ANOVA test including a covariate. In this excerpt of code we are testing for significant difference in the height with age as a covariate.

```
PROC GLM data=sw_ht;
  CLASSES trt;
  MODEL height=trt age age*trt/solution;
  MEANS trt/TUKEY lines; /*tukey test*/
  LSMEANS trt/pdiff; /*least squares means*/
RUN;
```

A.5.3 ANOVA with Nesting

The following SAS® code is for an ANOVA test including nesting. In this excerpt of code we are testing for significant differences in mean dbh between treatments with plots nested in treatments.

```
PROC GLM data=sw_dbh;
  CLASSES trt plot;
  MODEL dbh=trt plot(trt)/ss3; /*plot nested in treatment*/
  TEST h=trt e=plot(trt); /*test trt with the nesting factor*/
  MEANS trt/TUKEY lines e=plot(trt); /*tukey test with the nesting factor as the error factor*/
  RANDOM plot(trt)/test; /*the nesting factor is random*/
  LSMEANS trt/pdiff; /*least squares means*/
RUN;
```

A.6 Appendix VI (MGM Crop Plans)

The number of lines in the empirical tree lists used for the treatment projections are listed in Table A-3.

Table A-3: Number of lines in empirical tree lists

Treatment	Plot #	# of tree entries in tree list
'Clearcut'	11	3
	12	4
	21	4
	22	3
	31	3
	32	2
	41	3
	42	3
'100m Strip'	21	27
	22	26
	31	8
	32	20
	51	7
	52	25
	61	12
	62	17
'50m Strip'	11	19
	12	25
	21	12
	22	25
	31	14
	32	14
	41	22
	42	13
'Mod Shelter'	11	34
	12	30
	21	39
	22	26
	31	36
	32	31
	41	32
	42	21
'Uncut Control'	11	24
	21	32

The crop plans run in MGM for Chapter 4 are displayed in Table A-4 and Table A-5. In the treatment projection crop plan the stands are batch listed into MGM and are then simply grown for 95 years. A record is then requested at the end of the growth projection.

Table A-4: Treatment Projection Crop Plan

Crop Plans	Hotchkiss			Saved: 1446 Aug 06 2002									
-	Stand Age	Year	Event	Settings	-	-	-	-	-	-	-	-	-
			Crop Plans	CropPlansID := Hotchkiss									
			Notes										
			Crop Plan	CropPlanID := TREATMENT GROW									
			Options	Region := 1	SubRegion := 11	_MinDbh := -1	_topdib := 0	_StumpHt := 0	_VolumeLoss := 10	AllowIngrowth := False	Default_Sindex := 14 16 16 14	UsePLM := False	
	5	1998	Establish	SourceIndex := 7	StandAge := 5	Year := 1998	TreeSource := C:\Program Files\MGM2001\Workbooks\Batch\standlist.txt						
	5	1998	Grow	Schedule := 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5									
	100	2093	Record	Sheet := Stand									
	100	2093	End										

Table A-5: Simulation Crop Plan

Crop Plans — Control Simulation — Treatment — Saved: 1544 Aug 07 2002

Stand Age	Year	Event	Settings					
		Crop Plans	CropPlansID := Control Treatment Simulation					
		Notes						
		Crop Plan	CropPlanID := Simulation					
		Options	Region := 1	SubRegion := 11	_MinDbh := -1	_topdib := 0	_StumpHt := 0	_VolumeLoss := 0 AllowIngrowth := False Default_Sindex := 14 16 16 14 UsePLM := False
10	2010	Establish	SourceIndex := 5	StandAge := 10	Year := 2010	Seed := 0	StandParsList := [Aw 4 16 1500 1.8 0.2 2.5 0.2 0.8 *,Pb 4 16 750 1.8 0.2 2.5 0.2 0.8 *,Pj 5 14 100 2.3 0.5 2.1 0.4 0.8 *]	
10	2010	Grow	Schedule := 10					
20	2020	Regen	SourceIndex := 5	StandAge := 20	Year := 2020	Seed := 0.1976	StandParsList := [Sw 5 14 75 2.2 0.4 1.8 0.4 0.8 *]	
20	2020	Grow	Schedule := 10 10 10					
50	2050	Regen	SourceIndex := 5	StandAge := 50	Year := 2050	Seed := 0.1976	StandParsList := [Sw 5 14 1100 2.2 0.4 1.8 0.4 0.8 *]	
50	2050	Grow	Schedule := 10 10 10 10					
90	2090	Thin	RemRuleIndex := 4	RemAmtIndex := 3	RemovalAmt := 75	SpeciesIndex := "Aw	HtDbhRatio := False	
90	2090	Thin	RemRuleIndex := 4	RemAmtIndex := 3	RemovalAmt := 75	SpeciesIndex := "Pb	HtDbhRatio := False	
90	2090	Thin	RemRuleIndex := 4	RemAmtIndex := 3	RemovalAmt := 100	SpeciesIndex := "Pj	HtDbhRatio := False	
90	2090	Thin	RemRuleIndex := 6	RemAmtIndex := 3	RemovalAmt := 40	SpeciesIndex := "Sw	HtDbhRatio := False	
90	2090	Thin	RemRuleIndex := 3	RemAmtIndex := 3	RemovalAmt := 20	SpeciesIndex := "Sw	HtDbhRatio := False	
90	2180	Thin	RemRuleIndex := 5	RemAmtIndex := 3	RemovalAmt := 30	SpeciesIndex := "Sw	HtDbhRatio := False	
90	2180	Grow	Schedule := 10					
10	2100	Regen	SourceIndex := 5	StandAge := 10	Year := 2100	Seed := 0.1976	StandParsList := [Pb 4 16 3000 1.8 0.2 2.5 0.2 0.8 *,Aw 4 16 13000 1.8 0.2 2.5 0.2 0.8 *,Bw 4 16 100 1.8 0.2 2.5 0.2 0.8 *]	
10	2100	Grow	Schedule := 10					
20	2110	Regen	SourceIndex := 5	StandAge := 20	Year := 2110	Seed := 0.1976	StandParsList := [Sw 5 14 600 2.2 0.4 1.8 0.4 0.8 *,Pj 5 14 50 2.1 0.4 1.9 0.4 0.8 *]	
20	2110	Grow	Schedule := 10 10 10 10 10 10 10 10					
100	2190	End						

The first event is the stand establishment. The stand establishment is done at year 10. Table A-6 outlines the details to the original stand that is to eventually form the main overstory.

Table A-6: Establishment of main canopy summary (Year 10)

Species	Age (bh)	Site Class	Density	Mean DBH	SD DBH	Mean Height	SD Height	Rho
Aw	4	16	1500	1.8	0.2	2.5	0.2	0.8
Pb	4	16	750	1.8	0.2	2.5	0.2	0.8
Pj	5	14	100	2.3	0.5	2.1	0.4	0.8

A second event is used to bring in white spruce trees that are intended to contribute to the main canopy by the first stage harvest. The details of this white spruce layer are outlined in Table A-7.

Table A-7: Establishment of main canopy summary (Year 20)

Species	Age (bh)	Site Class	Density	Mean DBH	SD DBH	Mean Height	SD Height	Rho
Sw	5	14	75	2.2	0.4	1.8	0.4	0.8

These stand conditions are grown for 30 years, at which time a 'regen' event is used to emulate understory establishment. Table A-8 outlines the details of the understory that is being established.

Table A-8: Understory layer event summary (Year 50)

Species	Age (bh)	Site Class	Density	Mean DBH	SD DBH	Mean Height	SD Height	Rho
Sw	5	14	1100	2.2	0.4	1.8	0.4	0.8

At year 90 'Thin' events, intended to simulate the treatment activities, are conducted within MGM. Table A-9outlines the event details for each species component of the stand.

Table A-9: Thinning event summary (Year 90)

Species	Removal Rule	Removal Amount
Aw	% by density with tallest trees first	75%
Pb	% by density with tallest trees first	75%
Pj	% by density tallest trees first	100%
Sw	% by density evenly across the diameter distribution	40%
Sw	% by density biggest diameter trees first	20%
Sw	% by density biggest height/diameter trees first	30%

At year 100 the deciduous regeneration layer is added. Table A-10 outlines the details of this layer and its species components.

Table A-10: Regeneration layer event summary (Year 100)

Species	Age (bh)	Site Class	Density	Mean DBH	SD DBH	Mean Height	SD Height	Rho
Aw	4	16	13000	1.8	0.2	2.5	0.2	0.8
Pb	4	16	3000	1.8	0.2	2.5	0.2	0.8
Bw	4	16	100	1.8	0.2	2.5	0.2	0.8

At year 110 the conifer regeneration layer is added. Table A-11 outline the details of this layer and its species components.

Table A-11: Regeneration layer event summary (Year 110)

Species	Age (bh)	Site Class	Density	Mean dbh	SD dbh	Mean Height	SD Height	Rho
Sw	5	14	1200	2.2	0.4	1.8	0.4	0.8
Pj	5	14	100	2.1	0.4	1.9	0.4	0.8

Following the addition of the second cohort the stand is grown in MGM for an additional 100 years.